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Lining waste storage and disposal units is a primary method of establishing the release of liquid and gaseous waste components into adjacent areas. This manual provides current technological information about a variety of liner materials that may be used to contain hazardous wastes. Guidance is given to assist in the selection, installation, and maintenance of appropriate liners for specific types of wastes in particular storage or disposal units. Several test methods for determining waste/liner compatibility are included, and a case study analysis methodology for lined units is presented. Liner manufacturers and material sources are listed.

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LINING OF WASTE IMPOUNDMENT AND DISPOSAL FACILITIES

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FOREWORD

The Environmental Protection Agency was created because of increasing public and governmental concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is the first necessary step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources; to preserve and treat public drinking water supplies; and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research -- a vital communications link between the researcher and the user community.

This report describes and details the major aspects of liners for hazardous waste disposal facilities. Various procedures are presented as to the selection, manufacture, construction, and use of the major types of liners to minimize the possbility of adverse environmental impacts.

Francis T. Mayo
Director, Municipal Environmental
Research Laboratory

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Abstract

Lining waste storage and disposal units is a primary method to control the release of liquid and gaseous waste components into adjacent areas. This manual provides current technological information about a variety of liner materials that may be used to contain hazardous wastes. Guidance is given to assist in the selection, installation, and maintenance of appropriate liners for specific types of wastes in particular storage or disposal units. Several test methods for determining waste: liner compatibility are included, and a case study analysis methodology for lined units is presented. Liner manufacturers and material sources are listed.

A previous version of this document dated September 1980 was announced in the Federal Register for public comment on December 17, 1980. The new edition incorporates changes as a result of the public comments, and supersedes the September 1980 version. Comments on this revised publication will be accepted at any time. The Agency intends to update these TRDs periodically based on comments received and/or the development of new information. Comments on any of the current TRDs should be addressed to Docket Clerk, Room S-269(c), Office of Solid Waste (WH-562), U.S. Environmental Protection Agency, 401 M Street, S.W., Washington, D.C., 20460. Communications should identify the document by title and number (e.g., "Lining of Waste Impoundment and Disposal Facilities," SW-870).

PREFACE

Subtitle C of the Resource Conservation and Recovery Act (RCRA) requires the Environmental Protection Agency (EPA) to establish a Federal hazardous waste management program. This program must ensure that hazardous wastes are handled safely from generation until final disposition. EPA issued a series of hazardous waste regulations under Subtitle C of RCRA that is published in 40 Code of Federal Regulations (CFR) 260 through 265 and 122 through 124.

Parts 264 and 265 of 40 CFR contain standards applicable to owners and operators of all facilities that treat, store, or dispose of hazardous wastes. Wastes are identified or listed as hazardous under 40 CFR Part 261. The Part 264 standards are implemented through permits issued by authorized States or the EPA in accordance with 40 CFR Part 122 and Part 124 regulations. Land treatment, storage, and disposal (LTSD) regulations in 40 CFR Part 264 issued on July 26, 1982, establish performance standards for hazardous waste landfills, surface impoundments, land treatment units, and waste piles.

The Environmental Protection Agency is developing three types of documents for preparers and reviewers of permit applications for hazardous waste LTSD facilities. These types include RCRA Technical Guidance Documents, Permit Guidance Manuals, and Technical Resource Documents (TRDs). The RCRA Technical Guidance Documents present design and operating specifications or design evaluation techniques that generally comply with or demonstrate compliance with the Design and Operating Requirements and the Closure and Post-Closure Requirements of Part 264. The Permit Guidance Manuals are being developed to describe the permit application information the Agency seeks and to provide guidance to applicants and permit writers in addressing the information requirements. These manuals will include a discussion of each step in the permitting process, and a description of each set of specifications that must be considered for inclusion in the permit.

The Technical Resource Documents present state-of-the-art summaries of technologies and evaluation techniques determined by the Agency to constitute good engineering designs, practices, and procedures. They support the RCRA Technical Guidance Documents and Permit Guidance Manuals in certain areas (i.e., liners, leachate management, closure, covers, water balance) by describing current technologies and methods for designing hazardous waste facilities or for evaluating the performance of a facility design. Although emphasis is given to hazardous waste facilities, the information presented in these TRDs may be used in designing and operating non-hazardous waste LTSD facilities as well. Whereas the RCRA Technical Guidance Documents and Permit Guidance Manuals are directly related to the regulations, the information in these TRDs covers a broader perspective and should not be used to interpret the requirements of the regulations.

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CHAPTER 1

INTRODUCTION

Background

The Resource Conservation and Recovery Act (RCRA) of 1976, PL-94-580, directed EPA to issue regulations establishing performance standards applicable to owners and operators of facilities used to treat, store, or dispose of hazardous wastes. The goal of RCRA is to ensure that these facilities are designed, constructed, and operated in a manner that protects human health and the environment.

On May 19, 1980, EPA issued general standards that identified which wastes were hazardous and created a manifest system to monitor the movement of hazardous wastes from the point of generation to final disposition. These general standards also delineated basic performance objectives necessary to safely handle and control hazardous wastes during generation, transport, treatment, storage, and disposal. Specific standards for hazardous waste land treatment, storage, and disposal (LTSD) facilities were published on July 26, 1982.

The principal means of protecting the environment and human health is to prevent hazardous waste constituents from migrating out of the facility into other areas. To a great extent, this can be accomplished by controlling liquids. There are two avenues for controlling liquids. One is to minimize leachate generation by keeping liquids out of the LTSD unit, and the other is to prevent any liquids present in the unit from escaping into the surrounding environment.

Placing liners beneath the waste in LTSD units is a key element in controlling the escape of liquids. Liners must be viewed as components of a liquids control system and not the definitive system itself. A liner is a barrier technology that prevents or greatly restricts migration of liquids, thus facilitating their removal from the unit. No liner, however, can contain liquids for all time. Eventually liners will either degrade, tear, or crack and will allow liquids to migrate out of the unit. It is, therefore, important that other measures be taken to remove liquids from the unit during the time that the liner is most effective (i.e., during the active life of the facility). Leachate collection and removal systems and measures to remove free liquids at closure are the principal techniques used in conjunction with liners in an effective liquids control system. After closure of disposal units, a protective cap becomes the principal element in controlling liquids by preventing them from entering a unit, thereby reducing the potential for leachate generation.

Purpose

This Technical Resource Document provides information on the performance, selection, and installation of various lining and cover materials, based upon current technology.

The information is intended to assist the user in determining what liner material(s) would be effective in containing specific hazardous wastes or waste leachates. Effective control for disposal units means preventing hazardous waste constituents from moving either into or through the liner. For storage units where both the waste and liner system must be removed at closure, hazardous waste constituents are allowed to move into, but not through, the liner itself.

Essential factors to consider in selecting appropriate liner materials are

° compatibility of the specified wastes or waste leachates with liner materials;

° compatibility of liner materials with supporting and surrounding environmental elements at the unit site;

° service life or period of time that the liner will be expected to contain the specified wastes.

Cost analyses are described for selecting the most economical liner materials of those found to be appropriate for a given situation.

After the appropriate liner materials have been selected, proper fabrication, construction, and installation of the liner are critical processes that contribute to successful onsite performance of the liner system. Careless or inappropriate practices during these processes may cause otherwise exemplary liner materials to fail. Considerations for ensuring proper construction and installation of different liners and procedures for maintaining the integrity of the liner during daily operations are discussed.

Scope

Chapter 2 describes various types of hazardous wastes and the constituents that are aggressive toward different lining materials. Several industrial waste streams are described to illustrate the type of waste liquids that may be in contact with liners.

Lining technology and materials are presented in Chapter 3. These linings include remolded and compacted soils and clays, admixes, polymeric membrane liners, sprayed-on liners, soil sealants, and chemisorptive liners.

The performance characteristics of many liner materials under field conditions with various types of wastes are discussed in Chapter 4, particularly their compatibility with wastes, permeability to water and waste constituents, failure mechanisms, and estimated service lives. Several testing procedures for evaluating the waste/liner interaction, and some data from actual field units are given.

Chapter 5 deals with the design and construction of LTSD units using various types of lining materials. In particular, it discusses the installation of membrane liners and associated problems. Attention is given to the specific requirements for site and surface preparation and the placing of protective soil covers on membrane liners to prevent puncturing. Special problems associated with the design and construction of disposal units (i.e., landfills) and leachate generation above the liner are also discussed.

The operation, management, and maintenance of different disposal units are described in Chapter 6. Particular attention is given to the facilities that have membrane liners and ground-water monitoring. A plan for monitoring the liners is suggested. Standard operating procedures are discussed, and a section is included on inappropriate practices.

Chapter 7 outlines the historical costs of installing various liner materials for different types of wastes in different parts of the country.

In Chapter 8, several methods for selecting a specific liner or a group of satisfactory liners for a given containment unit are presented. These include the use of compatibility tests, moderate duration exposure tests, soil condition tests, prior performance in similar facilities, and costs.

Specifications for the construction of selected liners or groups of liners are suggested in Chapter 9.

For those wishing to obtain additional information on specific topics, each chapter lists references, and there is a complete bibliography at the end of the volume.

More detailed information on certain subjects is presented in the appendices. Appendix I is the Unified Soil Classification System. Appendix II lists companies that provide liner materials and services. Test methods are described in Appendix III. Other Appendices address flexible polymeric membrane liner installation, leachate collection systems, soil liner design, and specifications for flexible polymeric membrane materials. In addition, a methodology for case study analysis of liner units is discussed. Because of the diverse origins of liner technology and the broad spectrum of potential uses of this document, a glossary of terms related to liner technology by pertinent subject area is included.

This document refers to, but does not discuss, the following subjects:

1. Site selection, except when specific liners would be inappropriate.
2. Detailed discussion of methods of analysis of wastes, except for information on waste components that are aggressive to linings of all types.
3. Monitoring of ground water.
4. Attenuation of pollutants in the native soil below the liner.
5. Legal aspects.

The document attempts to bring together current knowledge and technology related to liners and the disposal of wastes. As new technology is developed and as experience in the use of liners provides more informatiom, this document will be modified and updated.

CHAPTER 2

CHARACTERISTICS OF WASTES AND WASTE LIQUIDS

2.1 INTRODUCTION

From the standpoint of pollution control, waste containment, and groundwater protection, we are primarily concerned with the waste liquids. Waste liquids carry dissolved components which, because the liquids are capable of migrating out of a disposal site, can enter and pollute the groundwater supply. Both the liquids and the dissolved components in a waste leachate may interact with a liner to alter its initially low permeability so that the polluting constituents can pass through the liner. Thus, the total composition of a waste liquid is important in the evaluation of an impoundment liner material for a given waste disposal facility.

According to a nationwide industry-sponsored survey (National Solid Waste Management Association, 1981) of land disposal practices conducted in 1980, the United States had a total of 12,627 active landfills. Of these landfills, only 40 were reported to operate with liners and only 26 were listed as having operational leachate treatment and control systems. The majority of the active landfills are for municipal solid waste (MSW) and generally do not accept industrial waste. In addition, the survey identified 109,839 active industrial waste surface impoundments of which 69,490 were on-site facilities. No information was reported on how many of these surface impoundments had liners or active leachate control.

Approximately 15% of all industrial wastes (57 million metric tons, wet weight, per year) is classified as hazardous (Hanrahan, 1979; EPA, 1980d). EPA-sponsored industrial studies conducted from 1975 through 1978 indicated that 78% of all hazardous waste in the United States is disposed of in unlined landfills or surface impoundments, whereas only 2% is disposed of in "secure landfills" (EPA, 1980b).

Cheremisonoff et al (1979) estimated that 90% by weight of industrial hazardous wastes are produced as liquids. These liquids are further estimated to contain solutes in the ratio of 40% inorganic to 60% organic. The heterogeneous nature of most wastes greatly complicates attempts to predict their effects on the integrity of disposal site liners. At the present state-of-the-art it is not possible to predict liner performance adequately based upon the composition of the waste liquid.

This chapter begins with a classification scheme for wastes according to the liquids and dissolved components present in a waste; then discussed are leachates generated by wastes, liquids that may be in the leachates, and the dissolved components that are carried by these liquids. Finally, the chapter presents examples of significant waste sources and the types of waste generated by these sources. Selected representative wastes of the following types are discussed:

- Municipal solid waste.
- Hazardous wastes from eight industries.
- Other nonradioactive wastes.

This discussion is intended only to be illustrative. The objective is to give examples of wastes from the different industries that may be encountered and which may or should be impounded in lined facilities. Interactions between wastes and specific liner materials are discussed in Chapter 4.

2.2 CLASSIFICATION AND GENERAL CHARACTERISTICS OF WASTE LIQUIDS AND LEACHATES

Wastes that are disposed of on land can be classified in a variety of ways. For example, they can be classified by industry source, by physical characteristics, and by chemical composition. Regardless of the type of waste, the important factor with respect to liners and their performance is the leachate or liquid generated by the waste and the composition of the leachate. Furthermore, the leachate generated in landfills can arise from two sources, i.e., from the waste itself and from water that enters the fill and leaches water soluble components.

Waste liquids generally fall into the following four classes: aqueous-inorganic, aqueous-organic, organic, and sludges, as shown in Table 2-1 (EPA, 1974a).

TABLE 2-1. PHYSICAL CLASSES OF WASTE LIQUIDS

Class of waste liquid	Solvent	Solute
Aqueous-inorganic	Water	Inorganic
Aqueous-organic	Water	Organic
Organic	Organic liquid	Organic
Sludges	Organic liquid or water	Organic and inorganic

Aqueous-inorganic liquid wastes are those in which water is the liquid phase and the dissolved components are predominantly inorganic. Examples of these dissolved components are inorganic salts, acids, bases, and dissolved metals. Examples of waste liquids in this category are brines, electroplating wastes, metal etching wastes, and caustic rinse solutions.

Aqueous-organic liquid wastes are those in which water is the liquid phase and the dissolved components are predominantly organic. Examples of these dissolved components are polar or charged organic chemicals. Examples of wastes in this class are wood preserving wastes, water-based dye wastes, rinse water from pesticide containers, and ethylene glycol production wastes.

Organic liquid wastes are those that have an organic liquid phase and the dissolved components are other organic chemicals dissolved in the organic liquid. Examples of this class of wastes are oil-based paint waste, pesticide manufacturing wastes, spent motor oil, spent cleaning solvents, and solvent refining and reprocessing wastes.

Sludges represent the fourth class of wastes. They are generated when a waste stream is dewatered, filtered, or treated for solvent recovery. Sludges are characterized by high solids content such as those found in settled matter of filter cakes and consist largely of clay minerals, silt precipitates, fine solids, and high molecular weight hydrocarbons. Examples of this class of waste are American Petroleum Institute (API) separator sludge, storage tank bottoms, treatment plant sludge, and filterable solids from any production or pollution control process.

Both economic and pollution control factors give impetus to solvent recovery and reductions in the discharge of liquid wastes. These factors make sludges the fastest growing class of wastes. After the placement of a sludge in a waste disposal facility, liquid or leachate migrates out of the sludge due to gravitational forces, overburden pressures, and hydraulic gradients. These leachates are similar in form to the first three classes of wastes shown in Table 2-1.

2.3 LIQUIDS GENERATED BY WASTE

Two types of liquids can be generated in a given waste (Anderson, 1981). These liquids are (1) the flowable constituents of the waste, which were either in the waste originally or generated by decomposition, and (2) the flowable material generated by water percolating through the waste and leaching soluble constituents (Figure 2-1).

The flowable components of the waste are often referred to as the primary leachate and include both the liquids in the waste and the dissolved constituents. A primary leachate may be aqueous-organic, aqueous-inorganic, or organic.

Leachate generated from water percolating through the waste is composed of water and the dissolved components or solutes. This flowable mixture is often referred to as secondary leachate and may be aqueous-organic or aqueous-inorganic, depending on the waste composition. Both forms of leachate combine at the bottom of the fill and would be in contact with the liner.

The predominant liquid in a leachate may be water or an organic liquid. The solutes in a leachate are either liquids or solids that dissolve in the liquid phase. Primary and secondary leachates each consist of a liquid carrier and dissolved constituents, both of which may affect the permeability of a liner, regardless of the type of liner.

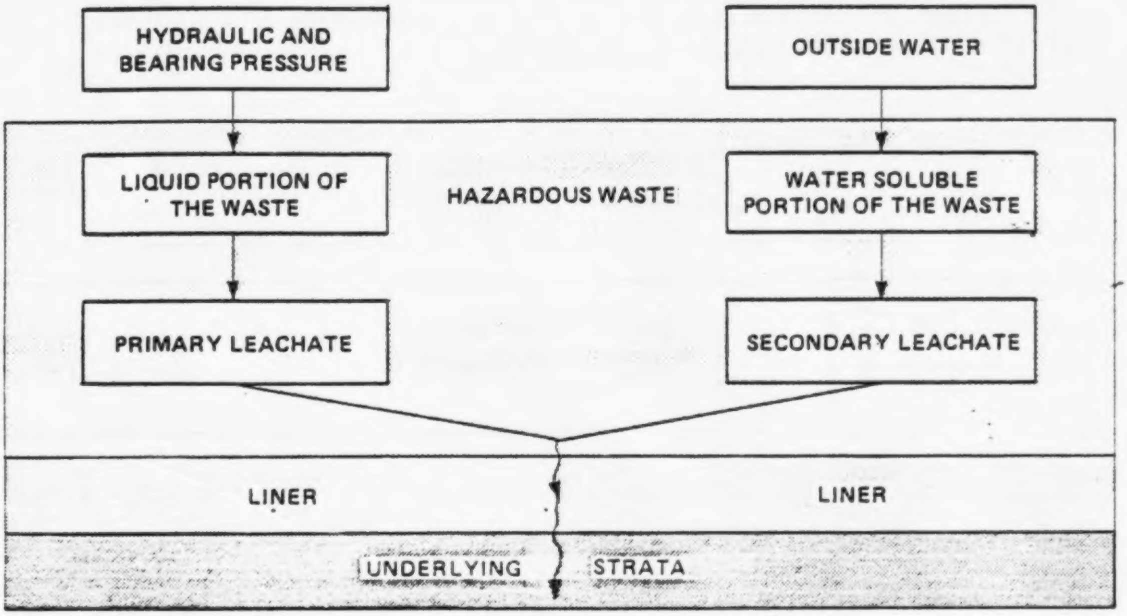
HYDRAULIC AND BEARING PRESSURE
OUTSIDE WATER
LIQUID PORTION OF THE WASTE
HAZARDOUS WASTE
WATER SOLUBLE PORTION OF THE WASTE
PRIMARY LEACHATE
SECONDARY LEACHATE
LINER
LINER
UNDERLYING
STRATA

Figure 2-1. Sources of primary and secondary leachates generated by wastes.

The liquid carrier will usually exert a dominating influence on the permeability of clay soil liners. However, dissolved constituents, whether inorganic or organic, can also affect the properties of a liner, depending upon the liner. For example, over long exposures, minor amounts of dissolved organics can affect asphaltic and some polymeric liners.

Essentially all available literature describing leachates generated in waste disposal sites considers water as the liquid carrier and organic chemicals to be present in only small quantities (Chian and DeWalle, 1977). While this may be the case at the interface of secondary leachate and a water table, the liquid phase at the interface of primary leachate and the disposal site liner will depend on the class of waste being disposed of. An organic waste or sludge with an organic liquid phase will most probably expose the liner to the organic liquids contained in the waste. The examples given in subsequent sections of this chapter show that the organic liquids disposed of in industrial landfills cover the spectrum of chemical species.

2.3.1 Liquids In Waste Leachate

For the purpose of experimentally determining or assessing the effects organic liquids may have on the integrity of a lining material, the liquids have been classified into four groups. These groups are based on the physical and chemical properties that govern their interactions with liner materials. These properties include acidity, basicity, polarity (Debye, 1929), and solubility parameters of the organic components (Hildebrand and Scott, 1950). The latter properties are of particular importance with polymeric and asphaltic liners. (Figure 2-2).

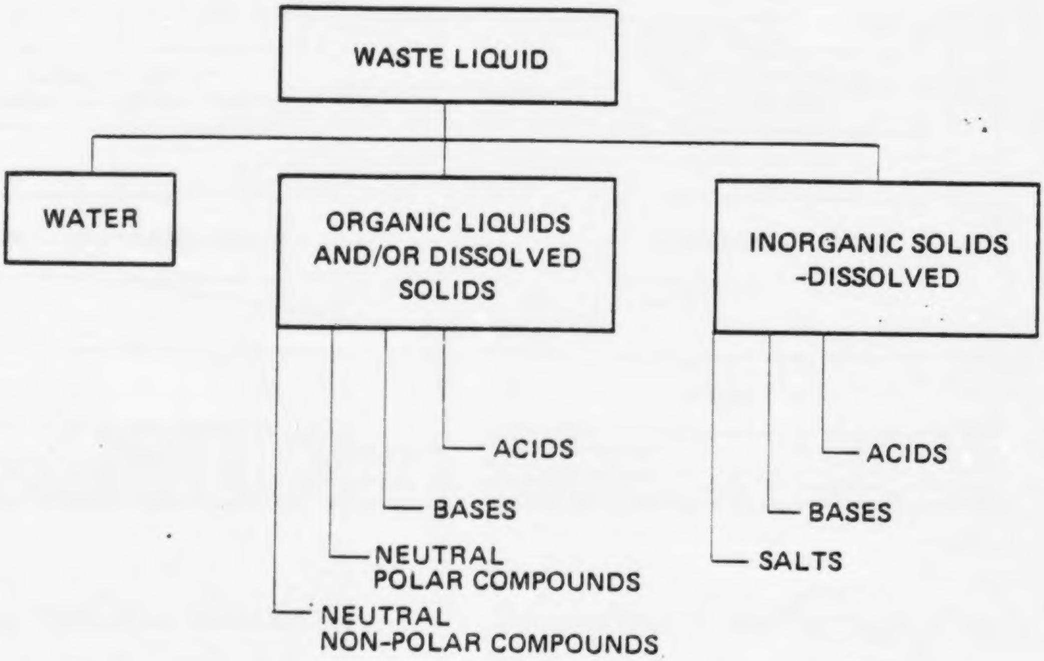
WASTE LIQUID
WATER
ORGANIC LIQUIDS AND/OR DISSOLVED SOLIDS
INORGANIC SOLIDS -DISSOLVED
ACIDS
BASES
NEUTRAL POLAR COMPOUNDS
NEUTRAL NON-POLAR COMPOUNDS
ACIDS
BASES
SALTS

Figure 2-2. Generalized composition of waste liquids that may contact a liner in service, showing the components that may be present. For actual wastes, the ratios of components will vary greatly but water is generally the principal component; the organics will be dissolved in the water as will be the inorganics. The liquid phase can be wholly organic with other dissolved organic liquids or solids and inorganics. Also, the organics could be present in emulsified or suspended states in the water.

Liquid organic acids are organic compounds with acidic functional groups, such as phenols and carboxylic acids. Proton-donating properties of Bronsted acids give these fluids potential to react with and dissolve soil liner components. An ever present source of liquid organic acids in municipal solid waste impoundments is anaerobic decomposition byproducts. These include acetic, propionic, butyric, isobutyric, and lactic acids. Anaerobic decomposition yields carboxylic acid derivatives of other organic liquids placed in the impoundment.

Brönsted organic bases (such as aniline) may be liquid and have been used as solvents in several industries. While it is not clear if organic bases are strong enough proton acceptors to dissolve soil liner components, inorganic bases are. Both inorganic acids and bases are discussed in the next subsection.

Neutral polar organic liquids do not exhibit a net charge but have an asymmetrical distribution of electron density resulting in an appreciable dipole moment, an indicator of polar character (Debye, 1929). Examples of such polar compounds are alcohols, aldehydes, ketones, glycols, and alkyl halides.

Neutral nonpolar organic liquids have no net charge and small, if any, dipole moments. These liquids have low water solubilities and little polarity. Examples of nonpolar organic liquids are aliphatic and aromatic hydrocarbons (Table 2-2).

Water has a large dipole moment and is present in all wastes to some extent. Water may infiltrate the cover of a disposal facility or be released from a waste as a decomposition byproduct.

In the case of polymeric liners, the relative solubility parameters of the polymer and the organic solvents that are present, either alone or in solution or dispersed in the water, can have major effects on the liner. When the solubility parameters of the solvent and the polymer are close, severe swelling of the liner and even dissolution can occur.

2.3.2 Dissolved Components in Waste Leachate

Organic and inorganic chemicals are dissolved in the leachate of a waste, regardless of the composition of the principal liquid of the waste. However, the relative abundance of a given dissolved component will depend on the composition of the principal liquid. For instance, if the liquid is neutral nonpolar organic, it will have a large carrying capacity for other neutral nonpolar organic chemicals. If the liquid phase is predominantly aqueous, its carrying capacity for nonpolar organics in its dissolved phase will be relatively small.

Water has a relatively large carrying capacity for polar organic chemicals (they may be miscible in each other in all proportions) and for inorganic acids, bases, and salts. Strong inorganic acids and bases, which are invariably water-based, may be especially aggressive to liner materials.

2.4 MUNICIPAL SOLID WASTE

2.4.1 Description of the Waste

Municipal solid waste (MSW), the refuse from residential and commercial sources, is typically composed of paper, glass, plastics, rubber, wood, metal,

TABLE 2-2. POTENTIAL ORGANIC CHEMICALS IN WASTE LIQUIDS

Relevant Physical and Chemical Properties

Organic chemicals			Temp. range of liquid state, °C								
Type		Name	Melting point	Boiling point	Density @ 20°C (gm/cm^3)	Viscosity @ 20°C (centipoise)	Dielectric constant @ 20°C	Water solubility @ 20°C (gm/L)	Vapor pressure @ 20°C (mm Hg)	Molecular weight	Solubility parameter,[a] $(cal/cm^3)^{1/2}$	Hydrogen bonding index
Acid	Aliphatic	Acetic acid	17	118	1.05	1.2	6.2	∞	11.4	60.05	9.2	20.0
Acid	Phenolic	Phenol	43	182	1.07	3.5[a]	9.8[b]	82.0	0.2	94.11	...	...
Base	Aromatic amine	Aniline	-6	184	1.02	4.5	6.9	34.0	0.3	93.13	11.8	18.1
Base	Alkyl amide	Formamide	2.6	210[c]	1.13	3.7	110	∞	<0.1	45.04	...	...
Neutral-polar	Alcohol	Methanol	-98	65	0.79	0.6	32.6	∞	92	32.02	14.5	18.7
Neutral-polar	Aldehyde	Butyraldehyde	-99	75	0.82	...	...	4.0	71	72.10	...	...
Neutral-polar	Alkyl halide	Chloroform	-63	61	1.49	4.7	8.0	8.2	160	119.38	9.3	1.5
Neutral-polar	Ketone	Acetone	-95	56	0.791	20.7	20.7	∞	185	58.08	10.0	9.7
Neutral-polar	Glycol	Ethylene glycol	-13	198	1.11	19.9	37.2	∞	<0.1	62.07	14.2	20.6
Neutral-nonpolar	Alkane	Heptane	-91	98	0.68	0.409	1.9	0.003	53.0	100.21	7.3[d]	0
Neutral-nonpolar	Aromatic	Benzene	5	80	0.88	0.652	2.3	1.8	76.0	78.11	9.2	0
Neutral-nonpolar	Alkyl benzene	Xylene	-47	139	0.87	0.810	2.6	0.20	6.5	106.16	8.8	0
Neutral-nonpolar	Mixed alkane	Paraffin oil	-8	321	0.87	28	30	...	...	-375	...	0
Water			0	100	1.0	1	78.5	∞	17.5	18.0	23.4	39.0

[a] At 50°C.

[b] At 60°C.

[c] Partial decomposition begins at 180°C.

[d] Normal hexane.

food and garden wastes, ceramics, rocks, textiles, leather, etc. Major components and rough wet weight percents are presented in Table 2-3 from Ham et al (1979). See Wigh (1979) for additional data. It is, however, the leachate produced by the waste, whether primary or secondary, that is of principal concern with respect to pollution and liner durability.

2.4.2 Characteristics of Leachate From Municipal Solid Waste

The leachate produced from municipal refuse is a highly complex liquid mixture of soluble, organic, inorganic, ionic, nonionic, and bacteriological constituents and suspended colloidal solids in a principally aqueous medium. It contains products of the degradation of organic materials and soluble ions which may present a pollution problem to surface and ground waters (Phillips and Wells, 1974). The quality of the leachate depends on the composition of the waste and the combined physical, chemical, and biological activities.

The precise composition of leachate is waste and site specific, depending on such variables as type of waste, amount of infiltrating water, age of landfill, and pH. Table 2-4 lists parameters of leachate which are used as analytical indicators of landfill leachate in the groundwater near a landfill (EPA, 1977). Tables 2-5 and 2-6 present data to show the complexity in composition of actual leachate from MSW, its site specific character, and its variation with time.

Griffin and Shimp (1978) compared the analyses of municipal landfill leachate with drinking water standards. Chemical oxygen demand (COD) and biochemical oxygen demand (BOD) of landfill leachates were generally high and the pH ranged from 4 to 9. Alkalinity, hardness, phosphate, nitrogen, heavy metals, and concentrations of other elements were also determined. The levels of these components varied over very wide ranges as shown in Tables 2-5 and 2-6.

Leachates generated in the disposal of hazardous wastes may include high concentrations of such heavy metals as mercury, cadmium, and lead; toxic substances, such as barium and arsenic; organic compounds, including chlorinated solvents, aromatic hydrocarbons, and organic esters; and various corrosive, ignitable, or infectious materials.

2.4.3 Potential Pollution by MSW Leachate

Municipal landfill leachates degrade groundwater quality by introducing the constituents shown in Tables 2-5 and 2-6, as well as biological contamination (Phillips and Wells, 1974).

The quantity of leachate produced is a function of the moisture content of the waste itself and the volume of water added through infiltration and percolation from surface and ground sources. Leachate is being recycled in some installations to enhance biodegradation in the landfill by providing nutrients and water. The quantity of leachate that leaves the landfill and the pollution potential are thus reduced.

TABLE 2-3. COMPOSITION AND ANALYSIS OF AN AVERAGE MUNICIPAL REFUSE FROM STUDIES BY PURDUE UNIVERSITY

Component	Percent of all refuse by weight	Moisture percent by weight[b]	Analysis (percent dry weight)[a]						
			Volatile matter	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Non-combustibles
Rubbish, 64%:									
Paper	42.0	10.2	84.6	43.4	5.8	44.3	0.3	0.20	6.0
Wood	2.4	20.0	84.9	50.5	6.0	42.4	0.2	0.05	1.0
Grass	4.0	65.0	...	43.3	6.0	41.7	2.2	0.05	6.8
Brush	1.5	40.0	...	42.5	5.9	41.2	2.0	0.05	8.3
Greens	1.5	62.0	70.3	40.3	5.6	39.0	2.0	0.05	13.0
Leaves	5.0	50.0	...	40.5	6.0	45.1	0.2	0.05	8.2
Leather	0.3	10.0	76.2	60.0	8.0	11.5	10.0	0.40	10.1
Rubber	0.6	1.2	85.0	77.7	10.4	...	...	2.0	10.0
Plastic	0.7	2.0	...	60.0	7.2	22.6	...	...	10.2
Oils, paints	0.8	0.0	...	66.9	9.7	5.2	2.0	...	16.3
Linoleum	0.1	2.1	65.8	48.1	5.3	18.7	0.1	0.40	27.4
Rags	0.6	10.0	93.6	55.0	6.6	31.2	4.6	0.13	2.5
Street sweepings	3.0	20.0	67.4	34.7	4.8	35.2	0.1	0.20	25.0
Dirt	1.0	3.2	21.2	20.6	2.6	4.0	0.5	0.01	72.3
Unclassified	0.5	4.0	...	16.6	2.5	18.4	0.05	0.05	62.5
Food Wastes, 12%:									
Garbage	10.0	72.0	53.3	45.0	6.4	28.2	3.3	0.52	16.0
Fats	2.0	0.0	...	76.7	12.1	11.2	0.0	0.00	0.0
Noncombustibles, 24%:									
Metals	8.0	3.0	0.5	0.8	0.04	0.2	...	...	99.0
Glass & ceramics	6.0	2.0	0.4	0.6	0.03	0.1	...	...	99.3
Ashes	10.0	10.0	3.0	28.0	0.5	0.8	...	0.5	70.2
Composite refuse, as rec'd:									
All refuse	100	20.7	...	28.0	3.5	22.4	0.33	0.16	24.9

Source: Ham et al, 1979.

[a] Analysis of the respective components.

[b] Moisture content of the respective component in the waste.

TABLE 2-4. PARAMETERS FOR CHARACTERIZING MSW LEACHATE

Physical	Chemical		Biological
	Organic	Inorganic	
Appearance	Phenols	Total bicarbonate	Biochemical oxygen demand (BOD)
pH	Chemical oxygen demand (COD)	Solids (TSS, TDS)	Coliform bacteria (total, fecal; fecal streptococcus)
Oxidation-reduction potential	Total organic carbon (TOC)	Volatile solids	Standard plate count
Conductivity	Volatile acids	Chloride	
Color	Organic nitrogen	Phosphate	
Turbidity	Tannins, lignins	Alkalinity and acidity	
Temperature	Ether soluble (oil and grease)	Nitrate-N	
Odor	MBAS	Nitrite-N	
	Organic functional groups as required	Ammonia-N	
	Chlorinated hydrocarbons	Sodium	
		Potassium	
		Calcium	
		Magnesium	
		Hardness	
		Heavy metals (Pb, Cu, Ni, Cr, Zn, Cd, Fe, Mn, Hg, As, Se, Ba, Ag)	
		Cyanide	
		Fluoride	

Source: EPA, 1977.

TABLE 2-5. COMPOSITION OF THREE MSW LANDFILL LEACHATES
Concentration of Constituents (mg/L), Except pH and Electrical Conductivity

	Source of data		
Constituent	Wigh, 1979	Breland, 1972	Griffin and Shimp, 1978
BOD$_5$	...	13,400	...
COD	42,000	18,100	1,340
TOC	...	5,000	...
Total solids	36,250	12,500	...
Volatile suspended solids	...	76	...
Total suspended solids	...	85	...
Total volatile acids as acetic acid	...	9,300	333
Acetic acid	...	5,160	...
Propionic acid	...	2,840	...
Butyric acid	...	1,830	...
Valeric acid	...	1,000	...
Organic nitrogen as N	...	107	...
Ammonia nitrogen as N	950	117	862
Kjeldahl nitrogen as N	1,240	...	...
pH	6.2	5.1	6.9
Electrical conductivity (µmho/cm)	16,000	...	...
Total alkalinity as CaCO$_3$	8,965	2,480	...
Total acidity as CaCO$_3$	5,060	3,460	...
Total hardness as CaCO$_3$	6,700	5,555	...
Chemicals and metals:			
Arsenic	...	...	0.11
Boron	...	...	29.9
Cadmium	...	...	1.95
Calcium	2,300	1,250	354.1
Chloride	2,260	180	1.95
Chromium	...	...	<0.1
Copper	...	...	<0.1
Iron	1,185	185	4.2
Lead	...	...	4.46
Magnesium	410	260	233
Manganese	58	18	0.04
Mercury	...	...	0.008
Nickel	...	...	0.3
Phosphate	82	1.3	...
Potassium	1,890	500	...
Silica	...	...	14.9
Sodium	1,375	160	748
Sulfate	1,280	...	<0.01
Zinc	67	...	18.8

TABLE 2-6. CHARACTERISTICS OF MSW LEACHATES[a]

Constituent	Reference[b] (mg/L)	Reference[c] (mg/L)	Reference[d] (mg/L)	Reference[e] (mg/L)	Reference[f] Fresh	Reference[f] Old
BOD$_5$	9-54,610	...	7,500-10,000	...	14,950	...
COD	0-89,520	100-51,000	16,000-22,000	500-1,000	22,650	81
Total dissolved solids	0-42,276	...	10,000-14,000	...	12,620	1,144
Total suspended solids	6-2,685	...	100-700	...	327	266
Total nitrogen	0-1,416	20-500	...	...	989	7.51
pH	3.7-8.5	4.0-8.5	5.2-6.4	6.3-7.0	5.2	7.3
Electrical conductivity (µmho/cm)	...	...	6,000-9,000	1,200-3,700	9,200	1,400
Total alkalinity as CaCO$_3$	0-20,850	...	800-4,000	630-1,730	...	...
Total hardness as CaCO$_3$	0-20,800	200-5,250	3,500-5,000	390-800	...	...
Chemicals and Metals:						
Cadimum (Cd)	...	...	0.4	...	...	...
Calcium (Ca)	5-4,080	...	900-1,700	111-245	2,136	254
Chloride (Cl)	34-2,800	100-2,400	600-800	100-400	742	197
Copper (Cu)	0-9.9	...	0.5	<0.04-0.11	0.5	0.1
Iron (Fe)	0.2-5,500	200-1,700	210-325	20-60	500	1.5
Lead (Pb)	0-5.0	...	1.6	...	...	...
Magnesium (Mg)	16.5-15,600	...	160-250	22-62	277	81
Manganese (Mn)	0.6-1,400	...	75-125	1.02-1.25	49	...
Phosphate (P)	0-154	5-130	...	21-46	7.35	4.96
Potassium (K)	2.8-3,770	...	295-310	107-242	...	...
Sodium (Na)	0-7,700	100-3,800	450-500	106-357	...	...
Sulfate (SO$_4$)	1-1,826	25-500	400-650	13-84	...	...
Zinc (Zn)	0-1,000	1-135	10-30	<0.04-0.47	45	0.16

[a] EPA, 1975a. [b] EPA, 1973. [c] Steiner et al, 1971. [d] Genetelli and Cirello, 1976. [e] Ham, 1975.
[f] Brunner and Carnes, 1974.

2.4.4 Potential Effects of MSW Leachate Upon Liners

MSW leachate is not inert toward lining materials; constituents of the leachate can affect liners in different ways, depending on their concentrations in the leachate and on the specific liner materials. Furthermore, the effects of the constituents can be synergistic and can vary with time as the concentrations change with the aging of the waste. Dissolved salts and ions may be damaging to some lining materials, particularly soils and clays. Acidity or alkalinity may dissolve components of soils or soil cements. Organic molecules (indicated by volatile acid content, volatile solid, and COD) can be damaging to rubber and plastic liners causing them to swell, to become more permeable and softer and lose in properties, such as tensile strength and tear resistance, and thus to be more easily torn and damaged. Water also can cause some liners to swell. These effects are discussed in detail in Chapter 4. Also discussed in Chapter 4 is the need for compatibility testing when the waste liquid or leachate is known to contain constituents that are aggressive to some types of liner materials.

2.4.5 Gas Production in MSW

Gases are also produced in the decomposition of organic matter in MSW landfills. These gases, primarily methane and carbon dioxide, may present problems if their migration is not controlled or if they are not collected. Methane is flammable, can be explosive, is damaging to plants and trees, and, in high enough concentration, may result in asphyxiation of animals and people; it is of commercial value as a heating fuel and some generated in MSW landfills is being used in this manner. Carbon dioxide is absorbed in leachate and tends to lower pH and thus to solubilize calcium, magnesium, and other metals.

2.5 HAZARDOUS AND TOXIC WASTES BY INDUSTRY

Industrial wastes are a major source of hazardous wastes, the components of the latter are usually heavy metals, strong acids or bases, and a large array of organic and inorganic chemicals. As shown in Table 2-7, taken from the EPA Report to Congress on the disposal of hazardous wastes (EPA, 1974a), each industry produces wastes with different characteristics and components. Also, wastes generated by the same industry vary from source to source. The chemical nature and reactivity, as well as concentration of the waste components, must be considered when choosing a liner for a specific waste storage or disposal facility. The characteristics of the wastes from several selected industries are discussed below, and are illustrative of specific wastes which may be encountered and may have to be placed in lined facilities. Special attention is given those constituents in the waste liquids that are aggressive to liners.

2.5.1 Electroplating and Metals Finishing Industry

The electroplating industry can be classified into three principal segments: plating, metal finishing, and the manufacture of printed circuit boards. The plating segment can be further subdivided into common metal electroplating, precious metal electroplating and electroless plating. Subsegments of the

TABLE 2-7. REPRESENTATIVE HAZARDOUS SUBSTANCES WITHIN INDUSTRIAL WASTE STREAMS

	Hazardous substances										
Industry	Arsenic	Cadmium	Chlorinated hydrocarbons[a]	Chromium	Copper	Cyanides	Lead	Mercury	Misc. organics[b]	Selenium	Zinc
Battery	...	X	...	X	X	...	...	...	...	...	X
Chemical manufacturing	...	...	X	X	X	...	...	X	X	...	...
Electrical and electronic	...	...	X	...	X	X	X	X	...	X	...
Electroplating and metal finishing	...	X	...	X	X	X	...	...	...	...	X
Explosives	X	...	...	...	X	...	X	X	X	...	...
Leather	...	...	...	X	...	...	...	...	X	...	...
Mining and metallurgy	X	X	...	X	X	X	X	X	...	X	X
Paint and dye	...	X	...	X	X	X	X	X	X	X	...
Pesticide	X	...	X	...	...	X	X	X	X	...	X
Petroleum and coal	X	...	X	...	...	...	X	...	...	...	...
Pharmaceutical	X	...	...	...	...	...	...	X	X	...	...
Printing and duplicating	X	...	...	X	X	...	X	...	X	X	...
Pulp and paper	...	...	...	...	...	...	...	X	X	...	...
Textile	...	...	...	X	X	...	...	...	X	...	...

Source: EPA, 1974a.

[a] Including polychlorinated biphenyls.

[b] For example: acrolein, chloropicrin, dimethyl sulfate, dinitrobenzene, dinitrophenol, nitroaniline, and pentachlorophenol.

metal finishing category include: anodizing, chemical conversion coating, chemical milling, etching, and immersion plating. Because of the heavy metal content of most wastes from the electroplating and metal finishing operations, many wastes from this industry may be hazardous; appropriate tests should be run to determine whether the waste liquids are hazardous.

In common metal electroplating, a ferrous or nonferrous basis material is electroplated with copper, nickel, chromium, zinc, tin, lead, cadmium, iron, aluminum, or combinations of these elements. Precious metal electroplating also uses either a ferrous or nonferrous basis material, but the metal plated onto the basis material is either gold, silver, palladium, platinum, rhodium, or combinations of these metals. Electroless plating is used on both metals and plastics.

Anodizing, coatings (e.g. chromating or phosphating), coloring, and immersion plating processes apply a surface coating to a workpiece for specific functional or decorative purposes. Chemical milling and etching processes are used to produce specific design configurations and tolerances on metal parts by controlled dissolution with chemical reagents or etchants.

Wastewaters from plating and metal finishing operations are discharged from all three phases of the electroplating process: workpiece pretreatment; the plating, coating, or basis material removal process; post treatment. Wastewaters are generated by rinse water disposal, plating or finishing bath dumping, ion exchange unit regenerant bleed streams, vent scrubber discharges, and maintenance discharges (EPA, 1979).

Treatment may involve degreasing with soaps, alkaline cleaning (sometimes with the aid of wetting agents), acid dipping, or, in the case of aluminum alloys, desmutting to remove finely divided particles of base material. The compositions of treatment cleaners (and thus, waste streams) vary with the type of base metal being cleaned and the kind of material being removed.

Wastewater constituents generated from the electroplating depend on the metals being plated and the plating solution used. Table 2-8 lists some of the various types of plating solutions used for electroplating. Plating solutions for the metals in the platinum group are proprietary. The most common plating solutions for electroless plating are copper and nickel, although iron, cobalt, gold, palladium, and arsenic are also used. Of particular concern among the constituents of electroless plating baths are the chelating agents, which are used to hold the metal in solution (so the metal will not plate out indiscriminately). There are three main types of chelating agents: amino carboxylic acids, amines, and hydroxy acids. One of the drawbacks in the use of chelating agents is the difficulty in precipitating chelated metals out of wastewater during treatment.

Wastes from metal finishing operations come from cleaning, pickling, anodizing, coating, etching, and related operations. The constituents in these wastes include the basic material being finished, as well as the components in the processing solutions. Baths used for anodizing, coating, and etching

TABLE 2-8. TYPICAL ELECTROPLATING SOLUTIONS

Plating compound	Constituents	Concentration, g/litre
Cadmium cyanide	Cadmium oxide	22.5
	Cadmium	19.5
	Sodium cyanide	77.9
	Sodium hydroxide	14.2
Cadmium fluoborate	Cadmium fluoborate	251.2
	Cadmium (as metal)	94.4
	Ammonium fluoborate	59.9
	Boric acid	27.0
	Licorice	1.1
Chromium electroplate	Chromic acid	172.3
	Sulfate	1.3
	Fluoride	0.7
Copper cyanide	Copper cyanide	26.2
	Free sodium cyanide	5.6
	Sodium carbonate	37.4
	Rochelle salt	44.9
Electroless copper	Copper nitrate	15
	Sodium bicarbonate	10
	Rochelle salt	30
	Sodium hydroxide	20
	Formaldehyde (37%)	100 mL/L
Gold cyanide	Gold (as potassium gold cyanide)	8
	Potassium cyanide	30
	Potassium carbonate	30
	Dipotassium phosphate	30
Acid nickel	Nickel sulfate	330
	Nickel chloride	45
	Boric acid	37
Silver cyanide	Silver cyanide	35.9
	Potassium cyanide	59.9
	Potassium carbonate (min)	15.0
	Metallic silver	23.8
	Free cyanide	41.2
Zinc sulfate	Zinc sulfate	374.5
	Sodium sulfate	71.5
	Magnesium sulfate	59.9

Source: Metal Finishing Guidebook and Directory, 1979.

usually contain metal salts, acids, bases, dissolved basis metals, complexing agents, and other deposition control agents. Bath constituents for chemical removal of basis metals include mineral acids, acid chlorides, alkaline ammonium solutions, nitro-organic compounds, and such compounds as ammonium peroxysulfate.

Post treatment processes in the plating segment encompass chemical conversion coatings (chromating, phosphating, and coloring), which are process steps for the metal finishing segment. Post treatment processes for metal finishing include: sealing and coloring of anodic coatings, bleaching or dyeing of chromate coatings, and chemical rinsing after phosphating.

Table 2-9 is a compilation of the various pollutants found in each subsegment of the electroplating industry. The concentrations presented are the range of values for each constituent, based on a statistical analysis of 50 metal finishing plants and 67 plating establishments (EPA, 1979).

Hallowell et al (1976) identified four waste streams as being destined for land disposal, i.e. water pollution control sludges, process wastes, degreasing sludges, and the salt precipitates from electroless nickel bath regeneration. Hallowell et al have estimated the quantities of these which could be generated in 1975, 1977, and 1983. These data are presented in Table 2-10.

2.5.2 Inorganic Chemicals Industry

The waste streams of a few of the specific industries in this category are briefly described in this subsection.

The chlor-alkali industry, whose main product is chlorine, also produces soda ash (NaOH) and potash (KOH) as co-products. Brine-purification sludges resulting from this industry contain mainly calcium carbonate, magnesium hydroxide, barium sulfate, and water. These slightly hazardous or non-hazardous wastes do not necessarily require strict landfilling precautions or procedures. Lead carbonate and asbestos waste products must be handled more carefully. Lead must be completely isolated from the environment before land disposal. Asbestos is insoluble, but the dust and small fibers present a serious potential health hazard. The surface of a disposal site for asbestos should be protected from wind and erosion. Chlorinated hydrocarbons and mercury are also by-products of certain processes.

The hazardous waste products from inorganic pigment manufacture include chrome and small amounts of mercury or lead. Most of the mercury, lead, zinc, and antimony is reclaimed. Minimally toxic wastes such as chlorides and nontoxic metal oxides from ore residues are usually disposed of in municipal sanitary landfills.

Other inorganic chemicals produce wastes such as ore residues, silicates or easily neutralized liquids. Most hazardous components are reclaimed or become part of a saleable by-product. Those hazardous components not

TABLE 2-9. CHARACTERIZATION OF WASTE STREAM FROM ELECTROPLATING INDUSTRY

Pollutant parameter	Segment of industry - Concentrations (mg/L)					
	Common metals plating	Precious metals plating	Electroless plating	Anodizing	Coatings	Chemical milling and etching
Copper	0.032-272.5		0.002-47.90			0.206-272.5
Nickel	0.019-2,954		0.028-46.80			
Chromium, total	0.088-525.9			0.268-79.20	0.190-79.20	0.088-525.9
Chromium, hexavalent	0.0005-534.5			0.005-5.000	0.005-5.000	0.005-334.5
Zinc	0.112-252.0				0.138-200.0	0.112-200.0
Cyanide, total	0.005-150.0	0.005-9.970	0.005-12.00	0.005-78.00	0.005-126.0	0.005-126.0
Cyanide, amenable	0.003-130.0	0.003-8.420	0.005-1.00	0.004-67.56	0.004-67.56	0.005-101.3
Fluoride	0.022-141.7		0.110-18.00			0.022-141.7
Cadmium	0.007-21.60					
Lead	0.663-25.39					
Iron	0.410-1,482				0.410-168.0	0.075-263.0
Tin	0.060-103.4				0.102-6.569	0.068-103.4
Phosphorus	0.020-144.0	0.020-144.0	0.030-109.0	0.176-33.0	0.060-53.30	0.060-144.0
Total suspended solids	0-10,000	0-10,000	0-40	36-924.0	20-5,300	0-4,300
Silver		0.050-176.4				
Gold		0.013-24.89				
Palladium		0.038-2.207				
Platinum		0.112-6.457				
Rhodium[a]		0.034				

Source: EPA, 1979.

[a] Only one plant had a measurable level of this pollutant.

TABLE 2-10. HAZARDOUS WASTES DESTINED FOR LAND DISPOSAL FROM THE ELECTROPLATING AND METALS FINISHING INDUSTRY (JOB SHOPS) - DATA IN METRIC TONS ON A DRY BASIS

Type of waste	1975	1977	1983
Water pollution control sludges	19,740	56,399	73,882
Process wastes	42,141	42,141	55,206
Degreaser sludges	5,434	5,434	7,118
Electroless nickel wastes	11,422	11,422	15,063
Total	78,737	115,396	151,269

Source: Hallowell et al, 1976.

reclaimed are usually disposed of in lined impoundment facilities (Hallowell et al, 1976).

2.5.3. Metal Smelting and Refining Industry

Smelting and refining of metal includes the following major operations and industry segments:

- Coking produces the residue (coke) by the destructive distillation of coal, which serves as a fuel and a reducing agent in the production of iron and steel.

- Steel production methods include open hearth, basic oxygen furnace, blast furnace, and electric furnace.

- Steel finishing involves a number of processes that impart desirable surface or mechanical characteristics to steel.

- Ferro alloy production produces the iron bearing products which contain considerable amounts of one or more alloying elements such as chromium, silicon, or manganese.

- Iron foundries mold or cast hot iron into desired shapes.

- Nonferrous metal smelting and refining involves the purification of nonferrous metal concentrates drawn from ores or scrap into refined metals and metal products.

A general list of the sources of potentially hazardous waste streams generated by metal smelting and refining and the constituents of these waste streams that are considered potentially hazardous or aggressive to lining materials are given in Table 2-11.

2.5.4 Organic Chemicals Industry

The petrochemical and organic chemicals industry is second only to petroleum refining in the volume of hazardous wastes it generates. Industrial petrochemical complexes and specialized organic chemical plants generate a wide variety of organic products and, as a result, each can generate an array of organic-rich hazardous wastes. The basic feedstocks for organic chemical producers are supplied principally by petrochemical plants and consist of gaseous and liquid fractions of crude oil produced in oil refineries. The feedstocks are used to manufacture "end use" organic products such as plastics, rubber, pharmaceuticals, paints, pesticides, organic pigments, inks, adhesives, explosives, soaps, synthetic fibers, and cosmetics. Many of the large petrochemical plants themselves also produce "end use" organic products such as pesticides, solvents, or heat transfer fluids.

Several of the segments of the organic chemicals industry, such as pesticides, pharmaceuticals, rubber, and plastics, are discussed individually in separate subsections.

The compositions of the waste streams are not well documented and many are considered to be proprietary. In addition, the waste streams can be a complex mixture of streams coming from different processes within a given plant; nevertheless, most of these waste streams will contain organic constituents as well as inorganic (EPA, 1975b).

2.5.5 Paint and Coatings Formulating Industries

The paint and allied products industries utilize many organic and inorganic raw materials, some of which are present in the wastes. There is no waste stream in the sense of wastes as by-products of production. The wastes come mainly from the packaging of raw materials, air and water pollution control equipment, off-grade products and spills, most of which is reclaimed and reused except for paint absorbed onto the final clean-up material. Coatings containing significant amounts of toxic metals are reworked and wastes contain little or no metallic residues. Most spoiled batches are incorporated in later batches whenever possible and spills are salvaged.

In the formulation of paint and coatings, a number of metal compounds are used as pigments; oils and polymer resins are used as bases and solvents are used as thinners. These ingredients become part of the waste as spoiled batches or spills. Such waste constitutes about 0.2% of production. Toxic chemical usage is strictly limited so a proportionally small amount of toxic substances (mainly mercury and lead) reach the waste stream from this source.

Waste wash solvents generally have higher boiling points and similar solvency to those used in the paint. Waste wash solvent is often retained and reused in later batches or is reclaimed by distillation or sedimentation on site. It may be sent to an outside contractor for processing and the recycled solvent is

TABLE 2-11. POTENTIALLY HAZARDOUS WASTE STREAMS GENERATED BY THE METAL SMELTING AND REFINING INDUSTRY

Product or activity	Waste stream	Constituents that are hazardous or aggressive to liners
Coking	Ammonia still lime sludge.	Oil and grease, cyanide, naphthalene, phenolic compounds, arsenic, heavy metals.
	Decanter tank tar sludge.	Oil and grease, phenol, naphthalene, pyrites, polyaromatics, nitrogen, heterocycles, heavy metals.
Electric furnace production of steel	Emission control dusts or sludges.	Heavy metals, e.g. chromium, lead, cadmium.
Steel finishing	Spent pickle liquor.	Heavy metals, e.g. chromium, lead, high pH.
	Sludge from lime treatment of spent pickle liquor.	Heavy metals, e.g. chromium, lead.
Ferro-chromium-silicon production	Emission control dust or sludge.	Heavy metals, e.g. chromium.
Ferro-chrome production	Emission control dust or sludge.	Heavy metals, e.g. chromium, lead.
Ferro-manganese production	Emission control dust or sludge.	Heavy metals, e.g. chromium, lead, manganese.
Gray and ductile iron foundry (Cupola furnace)	Emission control dust or sludge.	Heavy metals, e.g. cadmium, lead.
Primary copper smelting	Acid blowdown slurry.	Heavy metals, e.g. antimony, arsenic, lead, cadmium, copper, selenium, zinc.
Primary lead smelter	Surface impoundment solids.	Heavy metals, e.g. arsenic, cadmium, lead, mercury.
Primary zinc smelter	Wastewater treatment sludge or acid plant blowdown.	Heavy metals, e.g. arsenic, cadmium, selenium, zinc.
	Electrolytic anode slimes or sludges.	Heavy metals, e.g. lead, cadmium, zinc.
	Cadmium plant leach.	Heavy metals, e.g. lead, cadmium, zinc.
Primary aluminum smelting	Spent potliner (cathodes).	Heavy metals, e.g. copper, lead, cyanides, fluorides.
Secondary lead smelting	Emission control dust or or sludge.	Heavy metals, e.g. chromium, lead, cadmium, zinc.

Source: K. W. Brown and Associates, 1980, pp 368-376.

returned to the plant for reuse. Waste wash solvents are also incinerated and some are placed in drums that are landfilled.

Equipment used for water-thinned paints is cleaned with water and sometimes with detergent. The wash water is settled, used as a thinner for later batches of the same type of paint or, where acceptable, released to the muncipal sewer system. Wash water from very dark colors, experimental, or spoiled batches is usually placed in drums that are landfilled.

The potentially hazardous materials in paints include: inorganic metals such as arsenic, beryllium, cadmium, chromium, copper, cobalt, lead, mercury, selenium, asbestos, cyanides, and organic compounds, such as halogenated hydrocarbons and pesticides (WAPORA, Inc., 1975).

Of the total estimated waste stream of 389,000 metric tons generated by the paint and coatings industry, 24.6% is potentially hazardous, 3.6% is hazardous solvents, and 0.2% is toxic chemical compounds. A detailed list of waste components and quantities is available in the reference by WAPORA, Inc. (1975). The organic constituent of the solvent can be particularly aggressive to liners based on asphalt, polymers, and, in some cases, clay soils.

2.5.6 Pesticide Industry

The diverse nature of the pesticide industry and the wide distribution of the products make it difficult to analyze and assess the pollution impact of specific active ingredients and their finished formulations. For example, there were some 24,000 different formulations available from 139 manufacturers and 5,660 formulators as of February 1976. Over 50,000 different products are said to have been registered by the EPA. Each company that markets a given formulation of finished pesticide must have a registered label for it. Over 3,500 companies hold federal registrations for one or more products. In addition, many pesticides are registered for intrastate sale only; an estimated 2,000 pesticidal products are registered in California alone (Wilkinson et al, 1978).

Many pesticide wastes are aqueous solutions or suspensions of organic and halogenated organic compounds. Some biocide wastes are generated in the production of: Dieldrin, Methylparathion, Dioxin, Aldrin, Chlordane, DDD, DDT, 2,4-D, Endrin, Guthion, Heptachlor, and Lindane. Inorganic based wastes result from the production of arsenic, arsenate, and mercurial compounds. Thallium and thallium sulfate are found in rodenticide wastes (EPA, 1974).

Pesticide wastes result largely from the periodic cleaning of formulation lines, filling equipment, spills, area washdown, drum washing, air pollution control devices, and area runoff. Wash waters and steam condensates from cleaning operations are the sources of liquid waste from the formulation lines and filling equipment. Steam cleaning condensates and rinse waters from other processing units such as the mix tanks, drum washers, and air pollution control equipment are also sources of pesticide wastes. The scrubber waters themselves are a waste stream with area washdown, leaks, and spills making up the remaining principal sources.

The principal constituents of wastewaters from the pesticide industry are dissolved organics, suspended solids, dissolved inorganic solids, and variable pH. As stated above, the great variety of manufactured end products effectively precludes the presentation of a "general" waste composition chart or table. Again, it is the water and the dissolved constituents that may be aggressive toward liner materials.

Because of the great range of sizes of pesticide manufacturing plants, it is plausible to expect the following developments to occur with respect to the disposal of generated wastes. For the small generator, the produced waste, due to small total volume and small relative volume, might be accepted into a municipal wastewater management system. In such an instance, the pollution impact, if discernible, would be minor. For the large generator, the facility would probably have its own wastewater pretreatment or treatment system; in this case, the waste would most likely be partially treated, then concentrated. The concentrated waste would be disposed of in a landfill, or stabilized or containerized and then placed in a landfill.

2.5.7 Petroleum Refining Industry

Different waste streams generated by the petroleum refining industry vary with the refining process. Highly caustic sludges result from operations including washing, sweetening, and neutralizing. Spent caustic solutions are discharged from alkylation, and isomerization units, and LPG treating processes. The waste stream is roughly 3-3.5% NaOH by weight. Oily refinery sludges contain sand, silt, heavy metals, and an array of organic compounds in addition to oil and water. The oil content of such wastes ranges from 1-82% by weight. Refer to Table 2-12 for concentrations and quantities of several wastes resulting from refining processes.

The oils, organics, high pH, and high ion concentrations may all be harmful to landfill or disposal site liners. Compatibility studies should be made before installing liners for this class of waste (Landreth, 1978).

2.5.8 Pharmaceutical Industry

Wastes generated by the pharmaceutical industry include chemically and biologically derived components. Many biological wastes may be treated by standard wastewater treatment methods, others are incinerated or landfilled.

Wastes containing heavy metals, Cr, Zn, Hg, etc. are produced in limited quantities. The metals are recovered from these wastes and the residues are landfilled under carefully controlled conditions. Solvents are recycled or incinerated. Nonhazardous solid wastes which include biological sludge from wastewater treatment, aluminum hydroxide, magnesium, and sodium salts (McMahan et al, 1975) are usually landfilled.

The major waste producing processes are extraction and concentration (product-by-product), and equipment washings. See Table 2-13 for raw waste sources and constituents. Biological wastes result from the production of vaccines, serums, and other products derived or extracted from plant and animal sources.

TABLE 2-12. RANGES OF CONCENTRATIONS AND TOTAL QUANTITIES FOR REFINERY SOLID WASTE SOURCES
(All values in milligram per kilogram except where noted)

Parameters	Sludge from clarified once through cooling water	Exchange bundle clearing sludge	Slop oil emulsion solids	Cooling tower sludge	API/Primary clarifier-separator bottom	Dissolved air flotation float	Kerosene filter clays	Lube oil filter clays	Waste biosludge
Phenols	0.0-2.1	8-18.5	5.7-68	0.6-7.0	3.8-156.7	3.0-210	2.0-25.2	0.05-6.4	1.7-10.2
Cyanide	0.01-0.74	0.0004-3.3	0-4.6	0-14	0-43.8	0.01-1.1	Trace	0.01-0.22	0-19.5
Selenium (Se)	0.1-1.7	2.4-52	0.1-6.7	0-2.4	0-7.6	0.1-4.2	0.01-26.1	0 1-2.1	0.01-5.4
Arsenic (As)	0.1-18	10.2-11	2.5-23.5	0.7-21	0.1-32	0.1-10.5	0.09-14	0.05-1.4	1.0-0.6
Mercury (Hg)	0.42-1.34	0.14-3.6	0-12.2	0-0.1	0.04-7.2	0.07-0.89	0-0.05	0.04-0.33	0-1.28
Beryllium (Be)	0.013-0.63	0.05-0.34	0-0.5	Trace	0-0.43	0-0.25	0.025-0.35	0.025-0.5	Trace
Vanadium (V)	15-57	0.7-50	0.12-75	0.12-42	0.5-48.5	0.05-0.1	13.2-42	0.5-65	0.12-5
Chromium (Cr)	16.6-103	310-311	0.1-1325	181-1750	0.1-6790	2.8-260	0.9-25.8	1.3-45	0.05-475
Cobalt (Co)	5.5-11.2	0.2-30	0.1-82.5	0.38-7	0.1-26.2	0.13-85.2	0.4-2.3	1.3-5	0.05-1.4
Nickel (Ni)	20.5-39	61-170	2.5-288	0.25-50	0.25-150.4	0.025-15	0.025-15	0.25-22	0.013-11.3
Copper (Cu)	56-180	67-75	8.5-111.5	49-363	2.5-550	0.05-21.3	0.4-12,328	0.5-8.0	1.5-11.5
Zinc (Zn)	93-233	91-297	60-656	118-1,100	25-6,596	10-1,825	6.6-35	0.5-115	3.3-225
Silver (Ag)	0.84-1.3	Trace	0-20.1	0.01-1.6	0.05-3	0-2.8	0.02-0.7	0.013-1.0	0.1-0.5
Cadmium (Cd)	0-1.0	1.0-1.5	0.025-0.19	0.06-0.6	0.024-2.0	0-0.5	0.19-0.4	0.025-1.5	0.16-0.54
Lead (Pb)	17.2-138	0.5-155	0.25-380	1.2-89	0.25-83	2.3-1,320	4.25-12	0.25-2.3	1.2-17
Molybdenum (Mo)	0.5-33	1.0-12	0.25-30	0.25-2.5	0.25-60	0.025-2.5	0.012-8.8	0.025-0.05	0.25-2.5
Ammonium Salts (as NH_4^+)	0.01-13	5-11	0-44	0.07-14	0.05-24	8.7-52	ca 0.01	2-4	28-30
Benz-a-pyrene	0-1.8	0.7-3.6	0-0.01	0-0.8	0-3.7	0-1.75	1.7-1.8	0.02-0.2	Trace
Oil (wt.%)	0.24-17.0	8-13	23-62	0.07-4.0	3.0-51.3	2.4-16.9	0.7-5.6	ca.3.9	0.01-0.53
Total weight Metric tons/year	9.7-18.0	0.4-1.0	1.4-29.2	0.1-0.13	0.3-45	13.6-31.0	0.79-127	102-682	1.8-38.5

Continued

TABLE 2-12. (CONTINUED)

Parameters	Coke fines	Silt from Storm water runoff	Leaded tank bottoms	Non-leaded product tank bottoms	Neutralized HF alkylation sludge (CaF_2)	Crude tank bottoms	Spent line from boiler feedwater treatment	Fluid catalytic cracker catalyst fines
Phenols	0.4-2.7	6.3-13.3	2.1-250	1.7-1.8	3.2-15.4	6.1-37.8	0.05-3.6	0.3-10.5
Cyanide	Trace	0.48-0.95	Trace	0-14.7	0.21-4.6	0.01-0.04	0-1.28	0.01-1.44
Selenium (Se)	0.01-1.6	1.1-2.2	0.1-3.1	1.5-22.4	0.1-1.7	5.8-53	0.01-9.2	0.01-1.4
Arsenic (As)	0.2-10.8	1.0-10	63-455	Trace	0.05-4.5	5.8-53	0.01-2.3	0.05-4.0
Mercury (Hg)	0-0.2	0.23-0.36	0.11-0.94	0.41-0.04	0.05-0.09	0.07-1.53	0-0.5	0-0.16
Beryllium (Be)	0-0.2	Trace	Trace	0.025-0.49	0.012-0.13	Trace	Trace	0.025-1.4
Vanadium (V)	400-3,500	25-112	1.0-9.8	9.1-34.6	0.25-5	0.5-62	0-31.6	74.4-1,724
Chromium (Cr)	0.02-7.5	32.5-644	9.0-13.7	12.7-13.1	0.75-5	1.9-75	0.025-27.9	12.3-19
Cobalt (Co)	0.2-9.2	11.0-11.3	26.5-71	5.9-8.2	0.3-0.7	3.8-37	0-1.3	0.25-37
Nickel (Ni)	350-2,200	30-129	235-392	12.4-41	7.4-103	12.8-125	0.13-26.2	47.5-950
Copper (Cu)	3.5-5.0	14.8-41.8	110-172	6.2-164	2.5-26	18.5-194	0.22-63.2	4.1-336
Zinc (Zn)	0.2-20	60-396	1190-17,000	29.7-541	7.5-8.6	22.8-425	2.0-70	19-170
Silver (Ag)	0.01-3.0	0.4-0.6	0.05-1.7	0.5-0.7	0.12-0.25	0.03-1.3	0.05-0.7	0.5-8.0
Cadmium (Cd)	0.015-2	0.1-0.4	4.5-8.1	0.25-0.4	0.012-0.12	0.025-0.42	0-1.3	0-0.5
Lead (Pb)	0.5-29	20.5-86	158-1,100	12.1-37.3	4.5-9.6	10.9-258	0.01-7.3	10-274
Molybdenum (Mo)	0.1-2.5	6.3-7.5	0.5-118	0.25-18.2	Trace	0.025-95	0-0.05	0.5-21
Ammonium Salts (as NH_4^+)	No value	1.0	No value	0.2	Trace	2.0	Trace	No value
Benz-a-pyrene	Trace	0.03-2.5	0.02-0.4	0.3-0.9	No value	0-0.6	Trace	0-1.0
Oil (wt.%)	0-1.3	2.2-5.5	18.9-21	45.1-83.2	6.7-7.1	21-83.6	0.04-0.5	0.01-0.8
Total Weight Metric tons/year	0.06-4.2	2.7	0.2-1.3	34.7-77	28-67	0.14-0.26	28.5-214.7	0.65-23.6

Source: Stewart, 1978

TABLE 2-13. RAW WASTE CONSTITUENTS FROM THE PHARMACEUTICAL INDUSTRY
(g/kg Production)

	TDS	NO_3-N	Total P	Oil and grease	Cl	SO_4	Sulfide	Total Hard-ness	Ca	Mg	Cu	Phenol
Fermentation	5.990	4.68	22.0	413	1.260	274	(a)	294	123	30	0.005	0.15
Biological products and natural extractive manfacturing	895	0.02	7.3	3.62	211	277	(a)	...	36.4	...	0.12	0.073
Chemical synthesis	1.060	0.20	7.83	21.6	104	203	...	61.6	15.2	5.68	0.002	0.16
Formulation	11.3	0.053	0.15	0.78	2.51	0.52	0.007	5.82	1.01	...	0.001	...
Research	1.33	Trace	0.23	(a)	0.94	1.27	(a)	...	...	...	...	...

Source: Riley, 1974.

[a] Data not reported.

Fermentation and chemical synthesis wastes resulting from this industry frequently are a mixture of aqueous, organic, and inorganic constituents.

Thus, waste-liner compatibility studies are essential before lining a disposal site for this complex type of waste.

2.5.9 Pulp and Paper Industry

The companies that make up the pulp and paper industry are large, diverse corporations that produce pulp, paper, and paperboard. The activities of this industry that produce wastes include chemical wood pulping, wastepaper pulping, paper production, de-inking of recycled paper, paperboard production, electricity production, and wastepaper reclamation. The waste streams that are associated with these activities are wastewater-treatment sludge, bark and hog fuel wastes, coal and bark ash, and wastepaper reclamation wastes. Table 2-14 presents analyses of various sludges that are generated by the pulp and paper industry.

The pulping processes can be classified into chemical and mechanical processes However, it is the chemical pulping operations that generate the hazardous waste streams through the use of chemicals to separate the fibers from the lignin in the wood. The kraft or sulfate pulping process generates sludges high in chromium, lead, and sodium, as shown in Table 2-14. Fortunately, a large proportion of the plants using this process recycle many of their wastes, including the burning of the lignin as fuel.

Wastewater treatment sludges arise from primary treatment such as settling, filtration and flotation, and secondary treatment in activated sludge and aerated lagoons. The concentration of specific pollutants may vary widely, depending upon the fibers and processes used.

Most of the pulping plants produce their own electricity from coal, oil, and bark. The bark ashes that are generated contain a low content of toxic

TABLE 2-14. CHEMICAL ANALYSIS OF PRIMARY AND SECONDARY TREATMENT SLUDGES FROM THE PULP AND PAPER INDUSTRY

Constituent[a]	Primary and secondary sludge from semi-chemical pulping	De-inking sludge #1 (recycled paper)	De-inking sludge #2	Pretreatment sludge from paper coating	Board mill sludge	Combined primary and secondary sludge
Water (%)	90-96	77.06	...	86	...	40
Solids (%)	4-10	22.4	...	14	...	60
Ash (%)	1-2.5	...	...	...	...	40
COD	60,000-120,000	...	...	400,000	...	...
Phenol	5	...	...	...	...	...
PCB	<13	...	...	...	...	...
Oil and grease	1	...	...	...	...	...
Total nitrogen	1,400	...	...	...	...	4
Aluminum	...	21,300	...	100,000	...	...
Cadmium	1.5	32	...	...	...	4.6
Calcium	4,000-15,000	4,390	...	...	...	...
Chloride	...	332	...	...	...	...
Chromium	...	20	180	...	79	16
Copper	ND[b]	...	330	...	62	...
Iron	...	538	1,500	200,000	2,400	...
Lead	120	32	1,300	...	380	47
Magnesium	...	1,170	...	...	...	...
Manganese	250	16	...	...	...	1,146
Nickel	25	2.3	8	3,000	11	52
Phosphorous	...	310	...	...	...	2
Potassium	1,600	114	...	...	...	...
Sodium	1,400	146	...	...	...	...
Sulfate	120	0.03	...	...	...	...
Zinc	260	151	300	4,000	350	397

Source: Energy Resources Co. (1979) and EPA (1979)

[a] In ppm unless otherwise noted.

[b] ND = Not detected.

metals. The coal ashes are similar to those discussed under the electric power industry.

2.5.10 Rubber and Plastics Industry

The rubber and plastics industry includes the production and manufacture of several types of natural and synthetic polymers. The properties and constituents of environmental concern in the process waste streams are:

- Alkalinity
- Color
- Cyanides
- Dissolved solids (principally inorganic chemicals)
- Fluorides
- Nitrogenous compounds (organics, amines, and nitrates)
- Numerous organic chemicals
- Oils and greases
- pH
- Phenolic compounds
- Phosphates
- Sulfides
- Temperature
- Turbidity
- Aluminum
- Antimony
- Cadmium
- Chromium
- Cobalt
- Copper
- Iron
- Lead
- Magnesium
- Manganese
- Mercury
- Molybdenum
- Nickel
- Vanadium
- Zinc

The major pollutants in the wastewater from the rubber products industry are oil, grease, suspended solids, and extreme pH. The synthetic rubber industry has a wastewater of high COD and BOD contents; heavy metals, cyanides, and phenols are usually present in less than 0.1 mg/L concentrations (Riley, 1974). The oils, organics, and metal ions are all potentially damaging to various lining materials (Landreth, 1978). Concentrations of individual wastewater contaminants are frequently not reported, but the waste stream in general is characterized by COD, BOD_5, TSS, TDS, and TOC (Becker, 1974 and 1975).

2.5.11 Soap and Detergent Industry

Soap manufacturing produces wastes high in fatty acids, zinc, alkali earth salts, and caustic soda. Glycerine is formed as a by-product of soap production but much of this is recovered and recycled. Sulfuric acid and sulfonic acid are used in the preparation of some soaps; the pH of the wastes generated in these processes is very low. Soap production wastes also include alcohols and alkylbenzenes. The waste stream is generally high in COD, BOD_5, TDS, acidity, oil, and grease, as indicated in the EPA publication on soap and detergent manufacturing (Gregg, 1974), which is a good source of additional information on the manufacturing processes, waste constituents, and waste disposal techniques for this industry.

Soap and detergent industry waste is emphasized here due to the potential synergistic effects it may have upon a liner by creating a broader dispersion of pollutants from mixing.

2.6 OTHER NONRADIOACTIVE WASTES

Large amounts of nonradioactive wastes are generated by two major industries, the coal-fired electric power industry and the mining industry. These industries generate large quantitites of wastes, some of which are potentially hazardous and may have to be impounded in lined storage or disposal facilities. The wastes from both industries are characterized by their inorganic nature and trace metal content. Neither waste contains significant organic material. In view of the magnitude and variety of the wastes and the anticipated growth of the industries, some of the specific wastes are described and briefly discussed in the following subsections.

2.6.1 Coal-Fired Electric Power Industry

The wastes produced by this industry fall into two major groups. The first group consists of the following high-volume wastes: fly ash, bottom ash, flue gas desulfurization sludges and slurries, and combinations of these. The second group consists of a variety of low-volume wastes, some of which are hazardous. The latter group includes:

- Air preheater waste water.
- Coal pile drainage.
- Cooling water, once through.

- Cooling water, recirculating.
- Metal cleaning waste water:
  Boiler, fireside.
  Boiler, waterside.
- Water treatment wastes, especially brines.
- Miscellaneous wastes, such as equipment washdown, floor drainage, and sanitary wastes.

2.6.1.1 High-volume wastes

High volume wastes generated by electric utilities consist of the various types of ash produced during fuel combustion and the waste produced from flue gas desulfurization systems. Generally, the components of the high volume wastes are: fly ash, which is collected from the flue gas; bottom ash and boiler slag, which accumulate inside the boiler; and flue gas desulfurization (FGD) sludge, which is produced in the process of removing sulfur dioxide gas from the flue gas. Fly ash is usually an extremely fine powder, bottom ash consists of granular particles, while slag consists of fused ash deposits.

The amounts of ash produced from a given system are primarily dependent on coal characteristics and on ash collection efficiency. For example, most coal in the United States has coal ash content ranging between 6 and 20 percent depending on the coal source, thus actual amounts of ash produced at a particular site could vary by a factor of 3 to 4 for the same amount of coal burned. The proportion of fly ash to bottom ash is dependent on coal characteristics, coal preparation prior to combustion, and the type of boiler furnace used. The volume of FGD sludge also varies widely, since volumes are influenced by fuel sulfur content, the FGD process used, as well as additives to the sludge, such as lime, limestone, or fly ash.

Large quantities of ash (fly ash and bottom ash) are produced by coal-fired power plants with disposal by ponding (sluiced or wet ash) or by landfilling (dry ash collection and transport). For the most part, ashes are fine particles that do not interact with most liner materials. Table 2-15 presents data on ash pond liquids. Several documents (Engineering Science, 1979; EPRI, 1979 and 1980) present excellent background information.

Flue gas cleaning wastes include the previously mentioned fly ashes and desulfurization sludges. As much as possible, the water in desulfurization sludges is recovered and recycled within the process system. Flue gas desulfurization (FGD) sludges vary widely in composition and characteristics. Unstabilized FGD sludge is pseudo-thixotropic in most cases, thus posing a significant potential for pollution. Stabilized FGD sludge, in its many forms, is desirable because of improved structural stability, reduced moisture content, reduced total volume, reduced permeability, and improved handling (EPRI, 1980). The data presented in Table 2-16 show the range in values of several constituents and parameters for three different FGD systems. Additional data and information is available (EPRI, 1979 and 1980; Leo and Rossoff, 1978).

TABLE 2-15. ELEMENTAL MAXIMUM CONCENTRATIONS AND OTHER PARAMETERS IN VARIOUS WASTE STREAMS FROM COAL COMBUSTION

Element	Flyash pond	Bottom ash/ slag pond	Flyash overflow	Ash pond leachate
Al	8.80	8.00	5.30	...
Sb	0.012	0.012	0.03	0.03
As	0.023	0.015	0.02	0.084
Ba	0.40	0.3-3.0	0.30	40.0
Be	0.02	0.01	0.003	0.003
B	24.60	24.60	1.03	16.90
Cd	0.052	0.025	0.04	0.01
Ca	180.0	563.0	...	1.00
Cl	14.0	189.0	2,415	...
Cr	0.17	0.023	0.139	...
Co	...	0.70	...	...
Cu	0.45	0.14	0.09	0.092
F	1.00	14.85	10.40	17.30
Ge	...	...	0.10	<0.10
Fe	6.60	11.0	2.90	...
Pb	0.20	0.08	...	0.024
Li	0.40	0.08	...	...
Mg	20.0	102.0	156.0	...
Mn	0.63	0.49	0.02	<0.002
Hg	0.0006	0.006	0.0002	0.015
Mo	...	0.49	0.10	0.69
Ni	0.13	0.20	0.015	0.046
P	0.06	0.23	0.41	...
K	6.60	7.00	...	...
Se	0.004	0.05	0.015	0.47
Si	15.0	51.0	...	...
Ag	0.01	0.02	...	...
Na	...	294.0	982.0	...
Sr	...	0.80	...	...
Ta	...	0.02	...	...
Ti	...	0.02	...	...
V	...	0.02	0.20	<0.20
Zn	2.70	0.16	2.50	0.19
Zr	...	0.07	...	...
pH	...	...	...	...
TDS	820.0	404.0	3,328	...
TSS	256.0	657.0	100.0	...
Bi	...	0.20	...	...
SO_4	...	2,300	527	...

Source: EPRI, 1978, pp 94 and 95.

TABLE 2-16
RANGE OF CONCENTRATIONS OF CHEMICAL CONSTITUENTS IN FGD SLUDGES FROM LIME, LIMESTONE, AND DOUBLE-ALKALI SYSTEMS

Scrubber Constituent	Liquor Concentration mg/L (except pH)	Solids, mg/kg
Aluminum	0.03 - 2.0	...
Arsenic	0.004 - 1.8	0.6 - 52
Beryllium	0.002 - 0.18	0.05 - 6
Cadmium	0.004 - 0.11	0.08 - 4
Calcium	180 - 2,600	105,000 - 268,000
Chromium	0.015 - 0.5	10 - 250
Copper	0.002 - 0.56	8 - 76
Lead	0.01 - 0.52	0.23 - 21
Magnesium	4.0 - 2,750	...
Mercury	0.0004 - 0.07	0.001 - 5
Potassium	5.9 - 100	...
Selenium	0.0006 - 2.7	2 - 17
Sodium	10.0 - 29,000	48,000
Zinc	0.01 - 0.59	45 - 430
Chloride	420 - 33,000	9,000
Fluoride	0.6 - 58	...
Sulfate	600 - 35,000	35,000 - 473,000
Sulfite	0.9 - 3,500	1,600 - 302,000
Chemical oxygen demand	1 - 390	...
Total dissolved solids	2,800 - 92,500	...
pH	4.3 - 12.7	...

Source: Leo and Rossoff, 1978.

2.6.1.2 Low-volume wastes

Boiler cleaning wastes are produced intermittently, but this waste stream contains several components that are toxic and potentially aggressive to liners (Engineering-Science, 1979; EPA, 1974b, p 143; EPA 1980e, p 200). These components consist of both the chemicals used in the cleaning solution and the material removed from the heat transfer surfaces, some of which are shown in Table 2-17. There are two main types of cleaning operations: waterside and fireside. Waterside cleaning consists of cleaning the inside of tubes and other boiler water passages, usually by chemical means. Fireside cleaning is more mechanical, consisting of high pressure nozzles directed against the surfaces to be cleaned (EPA, 1974b, p 147). The cleaning solution often contains alkalis to dissolve oil and grease, and detergents to keep the removed material in colloidal suspension (Table 2-18).

Water treatment wastes can be classified into two categories: sludges from clarification, softening and filter backwashing operations; and waste brine from the several types of deionization processes. The composition of the first category depends on the raw water quality and method of treatment. Such sludges can usually be dewatered and the solid residue landfilled. The supernatant water can be recycled for other in-plant uses.

Wastes from deionization processes are characterized by a high dissolved solids concentration as shown in Table 2-19. Waste brines from the regeneration of ion exchange resins can also be highly acidic or alkaline depending upon the exchange resin being used. Such water is often neutralized and treated for suspended solids removal for subsequent use in other in-plant operations which can tolerate low quality water (EPA, 1974b, p 132; EPA 1980e, p 177).

Recirculating cooling wastewater or cooling tower blowdown is the bleed stream from the recirculation water cooling system. The cooling tower blowdown contains various chemical additives to prevent scale formation, corrosion and biological fouling of surfaces. The blowdown is relatively high in total dissolved solids, usually several times the concentration of the feedwater. The potential for pollutants in blowdown is high, thus most blowdown waters are ponded. In some cases, the blowdown water is used as feedwater or makeup water for sluicing ashes from boilers or for sulfur dioxide scrubbing solution (EPA, 1974b, p 115; EPA 1980e, p 44).

Wastes such as once-through cooling water and coal pile runoff, which do not generally discharge to lined ponds are not discussed in this document. Once-through cooling water is usually discharged to a receiving water body, coal pile runoff occurs only occasionally and its character is dependent on the type of coal, and miscellaneous wastes are generally discharged to a municipal wastewater treatment plant.

2.6.2 Mining and Refining Industries

The selection of specific process and waste streams for discussion reflects, in part, the available information and the relative importance of the specific streams with respect to future liner usage. There are other factors such as

TABLE 2-17. COMPOSITION OF BOILER BLOWDOWN

Pollutant	Concentration, mg/L
Conventional measures of pollution	
pH	8.3 - 12.0
Total solids	125 - 1,407
Total suspended solids	2.7 - 31
Total dissolved solids	1.08 - 11.7
BOD_5	10 - 1,405
COD	2.0 - 157
Hydroxide alkalinity	10 - 100
Oil and grease	1 - 14.8
Major chemical constituents	
Phosphate (total)	1.5 - 50
Ammonia	0.0 - 2.0
Cyanide (total)	0.005 - 0.014
Trace metals	
Chromium (total)	ca 0.02
$Chromium^{+6}$	0.005 - 0.009
Copper	0.02 - 0.19
Iron	0.03 - 1.40
Nickel	ca 0.030
Zinc	0.01 - 0.05

Source: EPRI, 1978, p 58.

total pollution potential, which were also considered. Tables 2-20 and 2-21 present estimates of solid waste production in mining industry segments, metals, and nonmetals (except coal), respectively. The columns on tailings indicate the portion of solid waste that is most likely to need lined impoundments. It is important to note that the data presented does not include the liquid component of tailings generation.

Mining process and waste liquids are generally highly complex materials usually containing water and a wide range of inorganic and organic dissolved constituents. Residues of the reagents used in froth flotation of ores to recover the valuable minerals and found in the aqueous portion of the tailing is shown in Table 2-22. Most of the organics, such as hydrocarbons, alcohols, and ethers that remain in the tailings water evaporate, decompose, or biodegrade. The inorganics generally are in low concentrations (Baker and Bhappu, 1974, p 77).

Individually, most of the constituents of mining process and waste liquids are well characterized as to their toxicity and pollution potential. The difficulty with these liquids is that they are complex blends of components that can act synergistically and be toxic and affect lining materials in a variety of ways different from individual constituents. Some liquids can also be highly concentrated and relatively simple. Analytical capabilities have

TABLE 2-18. FIRESIDE WASTEWATER CHARACTERISTICS

Constituent	Concentration (mg/L) Maximum	Average
Total chromium	15	1.5
Hexavalent chromium	<1.0	0.02
Zinc	40	4.0
Nickel	900	70
Copper	250	6.0
Aluminum	21	2.0
Iron	14,000	2,500
Manganese	40	3.5
Sulfate	10,000	1,000
TDS	50,000	5,000
TSS	25,000	250
Oil and grease	Virtually absent	

Source: EPA, 1980e, p 213.

TABLE 2-19. ION EXCHANGE REGENERATION WASTES

Pollutant	Mean value	Minimum value	Maximum value
pH (122 entries)	6.15	1.7	10.6
Suspended solids (mg/L) (88 entries)	44	3.0	305
Dissolved solids (mg/L) (39 entries)	6,057	1,894	9,645
Oil and grease (mg/L) (29 entries)	6.0	0.13	22

Source: EPA, 1980e, p 187.

developed greatly in recent years; therefore, an accurate compositional analysis can generally be made of any given liquid. The fluid must be characterized to determine its major constituents.

TABLE 2-20. ANNUAL SOLID WASTE PRODUCTION STATISTICS AT SURFACE AND UNDERGROUND MINES[a] - METALS

(In thousand short tons)

Industry segment	Mine waste[b]	Tailings[c]	Total	Percent of total for all non-coal minerals
Bauxite	11,500	1,400	13,000	<1
Copper	378,000	260,000	638,000	29
Gold	11,800	5,400	17,200	1
Iron	277,000	175,000	452,000	20
Lead	2,270	8,900	11,200	<1
Molybdenum	13,100	30,400	43,500	2
Silver	2,010	1,900	3,910	<1
Tungsten	210	1,750	1,960	<1
Uranium	306,000	16,200	322,000	14
Zinc	1,270	6,700	7,970	<1
Other[d]	17,000	(e)	17,000	1
Total	1,020,000	508,000	1,510,000	68

Source: PEDCO, 1981.

[a] Based on data obtained from 1978-79 Minerals Yearbook, U.S. Bureau of Mines.

[b] Includes overburden from surface mining operations and waste discarded on the surface from underground mining operations.

[c] Estimated by PEDCO from data in the 1978-79 Minerals Yearbook.

[d] Antimony, beryllium, manganiferrous ore, mercury, nickel, rare earth metals, tin, and vanadium.

[e] Quantitative information on these wastes are not compiled since relatively insignificant amounts are generated.

TABLE 2-21. ANNUAL SOLID WASTE PRODUCTION STATISTICS AT SURFACE AND UNDERGROUND MINES[a] - NONMETALS

(In thousand short tons)

Industry segment	Mine waste[b]	Tailings[c]	Total	Percent of total for all non-coal minerals
Asbestos	4,150	2,180	6,330	<1
Clays	43,000	0	43,000	2
Diatomite	(d)	(d)	(d)	(d)
Feldspar	192	920	1,110	<1
Gypsum	2,700	700	3,400	<1
Mica (scrap)	467	1,310	1,780	<1
Perlite	107	294	401	<1
Phosphate rock	420,000	136,000	556,000	25
Potassium salts	163	17,200	17,400	<1
Pumice	108	210	318	<1
Salt	(d)	1,100	1,100	<1
Sand and gravel	(d)	6,000	6,000	<1
Sodium carbonate (natural)	322	5,080	5,410	<1
Stone:				
Crushed or broken	82,400	0	82,400	4
Dimension	1,620	2,830	4,450	<1
Talc, soapstone, pyrophyllite	1,460	420	1,880	<1
Total	572,000	174,000	724,000	32

Source: PEDCO. 1981.

[a] Based on data obtained from 1978-79 Minerals Yearbook, U.S. Bureau of Mines.

[b] Includes overburden from surface mining operations and waste discarded on the surface from underground mining operations.

[c] Estimated by PEDCO from data in the 1978-79 Minerals Yearbook.

[d] Quantitative information on these wastes are not compiled since relatively insignificant amounts are generated.

TABLE 2-22. COMMON FLOTATION REAGENTS USED IN THE RECOVERY OF MINERALS FROM ORES

Reagent type and name	Chemical composition	Amount added	Reagents distribution		Toxic species
			Solids	Solution	
Collectors					
Xanthate	ROCSSH	<0.1	Mostly complexed	Minor	CS_2
Thiophosphates	$(RO)_2PSSH$	<0.1	Mostly complexed	Minor	$H_2PO_4^-$, HS^-, H_2S
Fatty acids	RCOOH	0.5 to 2.0	Complexed with minerals and ions	Minor	Biodegradable
Sulfonates and sulfates	RSO_3H RSO_4	0.5 to 2.0	Complexed with minerals and ions	Minor	Biodegradable (except cyclic)
Amines	RNH_2Acetate	0.2 to 2.0	Absorbed on silicates	Minor	Free amine[a]
Fuel oils	Saturated	0.1	Selectively absorbed	Minor	Volatile hydrocarbons
Frothers					
Pine oil	Aromatic alcohols	<0.1	Carried over in froth	Appreciable	Volatile, carcinogenic
Dow froth	Higher alcohols	<0.1	Carried over in froth	Appreciable	Volatile, biodegradable
MIBC	Methyl isobutylcarbinol	<0.1	Carried over in froth	Appreciable	Volatile, biodegradable
Conditioners					
Sodium sulfides	Na_2S, NaHS	1 to 15	Selectively complexed	Major	HS^-, H_2S, SO_4^-
Phosphorous pentasulfide	P_2S_5	1 to 4	Selectively complexed	Major	HS^-, H_2S
Sodium cyanide	NaCN	0.005 to 0.1	Mostly complexed	Minor	CN^-
Sodium silicate	Na_2SiO_3	0.2 to 1.0	Mostly complexed	Appreciable	H_4SiO_4
Milk of lime	$Ca(OH)_2$	1 to 4	Mostly complexed	Appreciable	OH^-
Separan	Polyacrylamide	<0.01	Mostly absorbed	Minor	Biodegradable

Source: Baker and Bhappu, 1974, p. 77.

[a] Unknown toxicity.

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CHAPTER 3

LINING MATERIALS AND LINING TECHNOLOGY

3.1 INTRODUCTION

The purpose of lining a waste disposal site is to prevent potentially polluting constituents of the impounded waste from seeping from the site and entering the groundwater or surface water system in the proximity of the site. The pollutants, as discussed in Chapter 2, include organic and inorganic materials, solids, liquids, gases, and bacteriological species. In their performance liners function by two mechanisms:

a. They impede the flow of leachates and thereby limit the movement of pollutants into the subsoil and thence into the groundwater. This requires a liner material having low permeability.

b. They absorb or attenuate suspended or dissolved pollutants, whether organic or inorganic, and reduce their concentrations so that they fall within the ranges set by the EPA for groundwater. This absorptive or attenuative capability is dependent largely upon the chemical composition of the liner material and its mass.

Most liner materials function by both mechanisms but to different degrees depending on the type of liner material and the waste liquid and its constituents. Membrane liners are the least permeable of the liner materials, but have little capacity to absorb materials from the waste. They can absorb organic material but, due to their small mass, their total absorption is small. Soils can have a large capacity to absorb materials of different types, but they are considerably more permeable than polymeric membranes. However, the greater the thickness of a given soil, the lower the flux through the liner. The choice of a particular liner material for a given site will depend upon many factors which are discussed throughout this Technical Resource Document. In this chapter, the major candidate materials for use as liners are discussed.

For the purpose of this Technical Resource Document, we consider a liner to be a material constructed or fabricated by man. Such a definition includes not only synthetic membranes and admixes but also soils and clays having low permeability which are (1) either brought to a site or available on the site and (2) remolded and compacted to reduce permeability.

Liners can be classified in a variety of ways, such as construction method, physical properties, permeability, composition, and type of service. These classifications are presented in more detail in Table 3-1. In this chapter, the various types of liner materials are discussed in the following classes:

- Soils and clays.
- Admixed materials.
- Polymeric membranes.
- Sprayed-on liners.
- Soil sealants.
- Chemisorptive liners.

TABLE 3-1. CLASSIFICATIONS OF LINERS FOR WASTE DISPOSAL FACILITIES

A. BY CONSTRUCTION:

- Fabricated on site:
    - Raw materials brought to site and liner constructed on site.
    - Compacted soil.
    - Mixed on site or brought to site mixed.
    - Sprayed-on liner.
- Prefabricated:
    - Drop-in polymeric membrane liner.
- Partially prefabricated:
    - Panels brought to site and assembled on prepared site.

B. BY STRUCTURE:

- Rigid (some with structural strength):
    - Soil.
    - Soil cement.
    - Concrete, including airblown concrete (shotcrete).
- Semirigid:
    - Asphalt concrete.
- Flexible (no structural strength):
    - Polymeric membranes.
    - Sprayed-on membranes.

C. BY MATERIALS AND METHOD OF APPLICATION:

- Compacted soils and clays.
- Admixes, e.g. asphalt concrete, soil cement.
- Polymeric membranes, e.g. rubber and plastic sheetings.
- Sprayed-on linings.
- Soil sealants.
- Chemisorptive liners.

For each type of lining material, characteristics and general features of the liner and the advantages and disadvantages are discussed.

3.2 SOILS AND CLAYS

3.2.1 Introduction

Due to their general availability, soils should be considered the first candidate material for the lining of a waste impoundment and disposal facility. Based on engineering, environmental, and economic criteria, an initial analysis should assess whether the native soil present at a site can be used to produce an effective liner. If the result of such an analysis is negative, other alternatives must then be explored.

A soil liner is the soil material which is native at or near the waste disposal site and which has been properly treated, remolded and/or compacted so that a flow-impeding layer of low permeabliity to wastes has been obtained.

Thus, low permeability and the retention of low permeability are, by far, the most important characteristics of a soil-liner. No matter how low the permeability is, a pollutant can still travel from the waste disposal site toward the groundwater via liner and underlying soil. To attenuate this effect, the soil liner has to possess the capacity of temporarily retaining the polluting species.

Both the low permeability and the high adsorption capacity are properties often associated with the presence of soil fines. Thus, as a general rule, one can state that the proportion of clay size particles (less than 2 μm) has to be one of the most significant criteria in the selection of a soil to be compacted as a soil liner. The reason a certain limiting value of clay size particles cannot be categorically stated is that both soil permeability and adsorption capacity are dependent on other factors apart from the proportion of fines. Among these, the gradation and the degree of weathering of the nonclay fraction, and the physicochemical and mineralogical properties of clay, are of considerable significance. Depending on these properties and on the required saturated hydraulic conductivity, which in general will be in the 10^{-9} to 10^{-6} cm s^{-1} range, the acceptable proportion of fines in a soil liner cannot be less than 25%.

In order to produce a soil liner that will function according to the design specifications, it is imperative to have a good understanding of the clay fraction. In a clay soil the hydromechanical behavior of the bulk soil depends on clay surface physicochemical characteristics; since these are determined by the clay mineral chemistry, the behavior of a clay soil can be understood only if the chemistry and the mineralogy of the clay fraction are carefully considered.

The compacted soil liner should be designed following a proper environmental analysis. Criteria have to be set forth and the functionality of the soil liner has to be assessed. If the environmental conditions have been analyzed and understood, and the design complies with all environmental requirements, the liner should function as desired.

3.2.2 Clay Properties

In the previous section the need was stated to consider clay properties relevant to the problem of constructing a clay-soil liner. Only an overall view of essential clay characteristics is presented in the next two sections. More detailed information on the properties of clays is available in some of the classical monographs, such as Grim, 1962; Grim, 1968; Marshall, 1964; Mitchell, 1976; Van Olphen, 1963; Yong and Warkentin, 1975.

3.2.2.1. Chemistry and mineralogy of clays

Table 3-2 presents some of the essential properties of kaolinite, illite and montmorillonite (smectite group) clays. In superficial soils, very seldom is the clay fraction totally dominated by only one of these three constituents. Furthermore, whether the characteristics presented in Table 3-2 will be significantly imparted to the soil of which they are a part depends on several other soil properties. The table shows the considerable difference in swelling potential between the three mineral species most likely to dominate the mineralogical composition of many soils. However, this is a "micro" behavior. The degree to which the bulk soil will react to this behavior depends on several factors among which the most prominent are: the clay proportion in the soil, the surface area of the nonclay fraction, and the geometry of the clay vis-a-vis the nonclay fraction (i.e. whether the clay coats the sand and silt or is mainly concentrated between the larger particles).

Among groups of clay minerals which are dominant in soils, the members of the kaolinitic group are very likely to behave as though they possess a "unique" structure, insensitive to the changes in hydration condition and the character of load application. The explanation for this behavior can be found in the structure and in the average size of kaolinite particles. This mineral is concentrated in the 0.5 to 2 μm range ("coarse" clay), which has a smaller surface area compared to other clay minerals. Furthermore, unlike many other clay mineral groups, the members of the kaolinitic group (1:1 minerals) possess no internal cleavage, successive tetrahedron/octahedron assemblages being linked by relatively strong hydrogen bonds. The lack of internal surface enhances the inactivity of kaolinitic clay minerals. The kaolinitic members are also chemically inactive because, unlike other minerals, they are almost perfect minerals, i.e. they display almost no isomorphous substitution. All of these facts make a kaolinitic clay quite invulnerable to changes in moisture condition. The kaolinitic structure is relatively rigid with no appreciable tendency to shrink or swell. Kaolinitic clay behaves, in many respects, like a finely-ground silt material.

Illite is characterized by the presence of "fixed" potassium ions in a twelve-fold coördination between two planes of oxygen atoms. The higher charge of the crystal unit combined with the perfect fit of the potassium ion in its cavity, promotes rigidity and impedes water penetration between crystal layers; consequently, only a limited swelling occurs. A second very important aspect of the presence of "fixed" or "nonexchangeable" potassium between successive layers is that, despite its high negative charge, i.e. its potentially high exchange capacity, the real cation exchange capacity (CEC) is

TABLE 3-2. TYPICAL VALUES FOR PROPERTIES OF KAOLINITE, ILLITE, AND MONTMORILLONITE[a]

Clay mineral	Particle dimensions, µm			Lattice thickness, nm	Charge deficiency[b] per unit cell	Surface area, m^2/g		Exchange capacity m equiv/100 g	
	Largest surface dimension	Thickness	$\frac{\text{Largest dimension}}{\text{thickness}}$			Theoretical	Water vapor	Cation pH = 7	Anion
Kaolinite (non-expansive 1:1 lattice)	0.3-4.0	0.05-2.0	...	0.74[c]	0	...	12[d]	3-15	5-20[e,f]
Illite (non-expansive 2:1 lattice)	0.1-0.3	>0.003	...	1.00	1.3-1.5[g]	...	52-82[d]	10-40	...
Ca-montmorillonite (limited expansion 2:1 lattice)	Not easily determinable, but smaller than the figures for illite.		10-100	0.96-1.80[h]	0.65	ca 750[i]	164-206[d]	80-150	10-30[e,f]
Na-montmorillonite (very expansive 2:1 lattice)	Not easily determinable, but smaller than the figures for illite		10-100	>0.96[j]	0.65	ca 750[i]	203-250[d]	80-150	10-30[e]

[a] Values from Grim, 1968, unless otherwise stated.

[b] Units are multiples of electrostatic units (esu). One charge = 4.8029×10^{-7} esu.

[c] Newnham, 1956; Brindey and Robinson, 1946.

[d] Johansen and Dunning, 1959.

[e] Hoffman et al, 1956.

[f] pH dependent.

[g] Grim et al, 1937.

[h] Frequently, two molecular layers of water with 1.45-1.55 nm.

[i] Van Olphen, 1963.

[j] Frequently, one molecular layer of water with 1.25 nm.

only a fraction of the potential one. The real CEC of the illite is intermediate between the CEC of kaolinite and that of smectite (montmorillonite).

Smectite (montmorillonite) has characteristically the smallest particle size of the three basic clay minerals. Typically the site of the negative charge is in the inner octahedral layer in which partial isomorphous substitution occurs; this generates a minimal cohesion between successive 2:1 layers, resulting in a very receptive and chemically active structure. Smectite (montmorillonite) readily absorbs polar organics or positively charged organic groups or inorganic ions. It exhibits the greatest surface area, CEC, and shrink-swell potential. In water, it can absorb on its interlayer surfaces 300% of its solid phase weight and consequently has the capacity for large shrinkage if the water is displaced by other liquids that yield a lower interlayer spacing.

Calcium montmorillonite adsorbs interlayer water to yield a stepwise increase in basal spacing from 1 nm (oven dry state) to about 2 nm (Theng, 1979). At 2 nm, the Ca-montmorillonite is fully expanded. With divalent cations such as calcium or magnesium adsorbed to its surfaces, montmorillonite resists dispersion and remains flocculated. While the flocculated state usually yields a higher permeability, its structure is more stable than the easily dispersed sodium saturated montmorillonite.

Sodium montmorillonite adsorbs interlayer water to yield a basal spacing from 1 nm (oven dry state) to over 5 nm (Theng, 1979). This increase in spacing represents a thickness of 4 nm for water on each surface. While this much interlayer expansion would at first appear advantageous for its ability to reduce clay liner permeability, the expansion is reversible and hence sodium montmorillonite is susceptible to shrinkage if it dries. Another problem with sodium-montmorillonite is that when it is fully expanded, it is susceptible to dispersion and internal erosion (see "Piping" in Chapter 4). A dispersed clay that lacks structural strength could flow as a viscous fluid if it is free to expand. This characteristic may cause problems such as loss of strength in waste impoundment side walls.

The description of the most significant characteristics of these three mineral species does not imply that all members of a particular clay mineral group have the same characteristics and properties. Thus, for example, the typical high swell/shrink behavior of the montmorillonite is explained in terms of the location of the isomorphous substitution in the crystal, which is the octahedral layer. However, there are members of the smectite group in which aluminum is substituted for silicon in the tetrahedral layer and only a limited tendency to volume change is to be expected.

The variability of properties in the smectite group is best revealed when comparing montmorillonite present in bentonite deposits located in geographically different regions. The bentonite is a rock found predominantly in tertiary and upper cretaceous deposits and is believed to have been formed from volcanic ash sedimented in marine environments. The smectites represent the main mineral group found in this rock.

The bentonite, due to its unique properties, is commercially used as a thickener in oil-well drilling fluids, as cement slurries for oil-well casings, as bonding agent in foundry sands and pelletizing of iron ores, as a sealant for canal walls, a thickener in lubricating greases and fireproofing compositions, in cosmetics, as a decolorizing agent, as a filler in ceramics, refractories and paper coatings, as an asphalt modifier, as polishes and abrasives, as a food additive, and as a catalyst support.

Most of the bentonite deposits that have been investigated contain Ca-saturated montmorillonite. A bentonite mined in Wyoming, the most investigated of all bentonites, contains Na-montmorillonite. The montmorillonite in Wyoming-type bentonite is a unique mineral as proven by the fact that the saturation with sodium ions of an ordinary montmorillonite does not result in the conversion to Wyoming montmorillonite (Grim, 1968). Some of the unique characteristics of the mineral are related to its crystalline structure and are probably a reflection of its unique origin.

In using the commercial bentonite for waste impoundment, the most important characteristic to be considered is the nature of exchangeable cations in the mineral and the extent of saturation with it. Only bentonite containing Na-montmorillonite should to be accepted as a liner material or as a component in an admix liner, because of the close correlation between the permeability of the clay and the exchangeable sodium percentage.

The permeability of three clays as a function of exchangeable calcium and sodium contents is shown in Figure 3-1. Yong and Warkentin (1975) observed that clays with divalent cations are, in general, more permeable than those with monovalent cations adsorbed onto interlayer surfaces. This effect is the same in all clays but is most pronounced in smectite (montmorillonite).

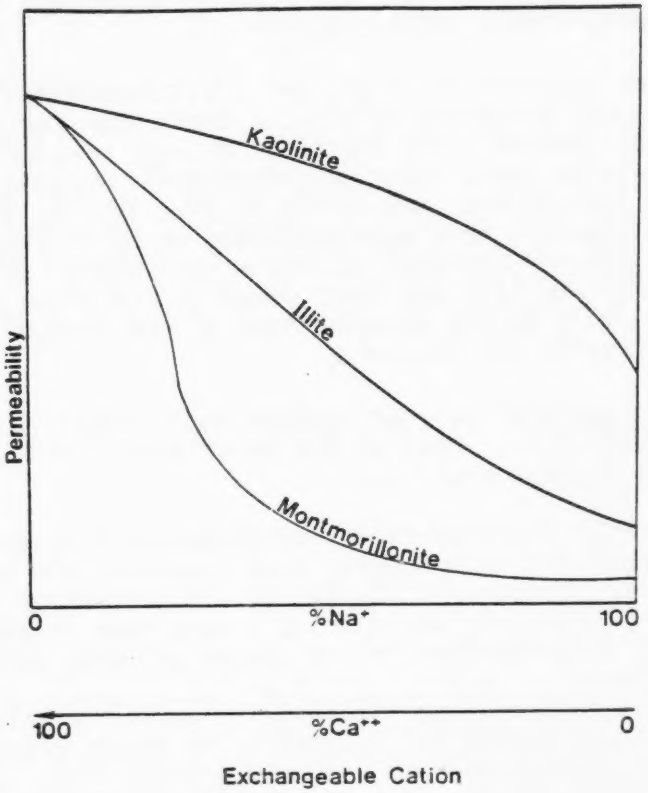

Figure 3-1. Relative permeability values for three clays with variable percentages of calcium and sodium on exchange sites (Yong and Warkentin, 1975).

Quirk (1965) found that permeability of sodium saturated montmorillonite decreased when the concentration of NaCl in the percolating solution was decreased. A similar clay saturated with calcium showed no appreciable decrease in permeability with a decrease in the calcium concentration of the percolating solution. Quirk and Schofield 1955) showed larger permeability decreases with decreasing electrolyte concentration in the percolating solution for clays with higher percentages of sodium on the exchange sites.

Blackmore and Marshall (1965) found that increasing sodium chloride concentrations in a liquid passing through a film of sodium saturated montmorillonite suppressed the double layer. The diminished double layer effect inhibited swelling while it decreased interlayer spacing and permeability.

3.2.2.2 Attenuation Properties of Soil Liners

As indicated in the introduction to this chapter, the two main functions of a soil liner are (1) to impede the flow percolating through it, and (2) to retain the polluting species of the waste effluent. The first will be given priority and will be extensively discussed in subsequent chapters. The second will be discussed briefly in this section.

The attenuation capacity of clays and clay-containing soils is mainly the capacity of these materials to absorb ionic species stoichiometrically, particularly the cations. The questions of why, how, to what extent, and how fast these reactions occur have been thoroughly investigated in the field of soil chemistry for cations such as Na, K, NH_4, Ca, Mg, Ba, and a few others. Very few investigations have been performed on the transport and retention of ionic species that are relevant to the waste disposal problem. Furthermore, the field conditions have not been properly simulated in experimental studies. The following points describe some of the limitations of the presently available information and its use:

- The transport of solutes through soil liners is likely to occur as unsaturated flow. Most of the experimental work performed on columns was done as saturated flow.
- Often, column experiments are performed at unreasonably large hydraulic gradients. It is unlikely that reducing the residence time of a particular solute will result in data directly transferable to the field, although the provision is always made to assess the soil/solute reaction as a function of the number of pore volumes (Fuller, 1978).
- Often, a polluting constituent is present in the percolate at a low concentration beyond our capability to detect properly and monitor the soil/solute interaction. At the present time, we lack the data in this concentration range. It is questionable whether adsorption isotherms carried out at relatively large concentrations can be extrapolated in the low range of concentrations.
- It is probably impossible to simulate a waste effluent and its complex chemistry. The results obtained in the laboratory with relatively simple liquids will indicate only trends in the possible behavior of a pollutant under a waste disposal site.

The attenuation capacity of soils for cationic and anionic chemical species, e.g. Cd, Co, Hg, Ni, Pb, and As, Cr^{6+}, Se, and V, seems to be, in a more complex manner, associated with soil ion adsorption capacity. In a comprehensive study on the subject (Fuller, 1978), no significant correlation was found between the retention of these elements and the exchange capacity of 11 soils, in spite of the close relationship between retention and the proportion of clays in these soils. Further studies are required to generate breakthrough curves (C/Co vs distance or time) for polluting constituents and potential contaminants.

These data are needed as input information for solving the mass transport-dispersion equation including a sink-source term (Kirkham and Powers, 1972; Freeze and Cherry, 1979).

Modeling the functionality of soil/waste or soil/chemical species systems has been done (Lowell, 1975; Fuller, 1978). Such an analysis requires an accurate assessment of the particular interaction between the specific wastes and soil under consideration.

Available experimental data have not generated the knowledge required to quantify the multitude of possible interactions between soils (soil properties) and wastes (chemical species). When these data become available, the designer of a soil liner should only identify relevant soil properties (clay content, clay physicochemical and mineralogical characteristics, free iron oxides, sparingly soluble salts, etc) and polluting species in the waste likely to produce contamination. Accounting for the flux rates likely to occur through the liner, the designer should then identify the types of breakthrough curve expected during flow (Fuller, 1978). This information can be used in the mass transport-dispersion equation to calculate the concentration of polluting species as a function of distance, time, and original concentration at the boundary between the liner and the waste.

3.2.3 Engineering Characteristics of Clay Soils

In this section, the following four characteristics of soils are discussed:

- Atterberg limits.
- Compactibility.
- Volume changes.
- Permeability.

The significance of these characteristics to the problem of waste confinement is emphasized.

3.2.3.1 Atterberg limits

The plastic and the liquid limits are essential tools in engineering work for classifying and characterizing clay soils. This is reflected in the emphasis on plasticity parameters in the classification of fine soils using the Unified Soil Classification System (Appendix I). The consistency of a given soil varies with moisture content, particularly with soils containing larger proportions of clay.

The plastic limit is the soil moisture content just below which the soil is friable and just above which the soil is plastic (it can be molded as a paste which exhibits a permanent set). The liquid limit is the soil moisture content just below which the soil is barely plastic and just above which the soil flows. At the liquid limit, soil behavior is a blend of plastic deformation (tends to cease deformation upon stress removal) and liquid flow (deforms freely after stress removal).

The plasticity test generates results in terms of mechanical behavior determined largely by the chemical and mineralogical properties of the clay in the soil.

The "Atterberg Limits" is a test that helps in classifying the soil and, consequently, weighs heavily in the decision-making process; it will help determine if the waste disposal site is covered by a soil that can be used as a soil liner. Soils that belong to the groups CL or CH should be considered the most suitable. Probably the most favorable soils are those with a liquid limit between 35 and 60, placed above the A-line in the PI vs LL chart of the Unified Soil Classification (Appendix I).

The informative power of this test can be increased by coupling it with knowledge of the clay content, i.e. the percentage of particles less than 2 μm in diameter. The concept of "activity", introduced by Skempton (1953), normalizes the plastic effect per unit weight of clay. Since this has been found to be characteristic of any particular clay (Skempton, 1953) depending on the type of clay (Mitchell, 1976), quick information regarding the type of clay in the soil can be obtained without resorting to x-ray analysis or other more quantitative mineralogical analyses.

The usefulness of plastic and liquid limits in geotechnical work can hardly be overemphasized because the limits are highly correlated with the quality and quantity of the clay fraction, which in turn control geotechnical properties in clay soils. Thus, compressive and shear characteristics are greatly affected by the clay content. Consolidation is a behavior strictly associated with clay soils. Shrink and swell characteristics have been correlated with Atterberg limits. Finally, soil flow properties are affected by the clay content. In many instances, knowledge of the Atterberg limits of a given soil leads to a fair estimate of the particular geotechnical behavior of interest.

The Atterberg limits are the result of a reaction between the clay phase of a soil and water. Consequently, the composition of both soil and water has an effect on the plastic behavior of the soil; thus, soil plasticity is a system property rather than a soil property, an idea suggested by Goldschmidt as early as 1926 (Goldschmidt, 1926). Subsequent studies (Warkentin, 1961) indicated that a Na-montmorillonite had a liquid limit almost three times larger when water was the liquid used rather than a molar solution of NaCl.

It has been also shown that the Flow Index (the negative slope of water content vs logarithm of number of blows in Casagrande's device) depends upon the nature of clay minerals and upon electrolyte concentration (Yong and Warkentin, 1975, p. 64).

In our studies on the subject, we used soils containing between 25% and 45% clay size particles (<2 μm). Solutions of NaCl and $CaCl_2$ in water were used as the soil mixing liquid. A combination of two levels of salt concentration, 2 and 50 $g\ L^{-1}$, and two levels of sodium adsorption ratio (SAR), 2 and 20 $(mmoles/L)^{1/2}$ yielded results which reinforced the idea that fluid chemistry has a significant influence on the liquid limit. The following conclusions were reached:

1. The higher the proportion of fines in a soil, the larger the effect of liquid chemistry.

2. The value of the liquid limit is more affected by liquid chemistry than is the flow index.

3. In a soil containing montmorillonite, both the SAR and the total salt concentration (TSC) significantly affected plastic characteristics. The higher the SAR and the lower the TSC, the larger the liquid limit.

4. In a predominantly kaolinitic soil, the lower the TSC, the higher the liquid limit.

In this example, only two liquid-phase characteristics were investigated. It is, however, to be expected that other characteristics like pH, abundance of non-native ionic species and chelating agents, density, viscosity, dipole moment, dielectric constant, etc, may have a significant impact on the fabric geometry of a soil and thus on the limits and on relevant geotechnical characteristics.

As indicated in the previous paragraph, the effects of industrial waste effluents generally differ from those of water; therefore, the determination of the limits using ASTM D423-66, "Liquid Limit of Soils", will not suffice as it calls for the use of distilled water. In most geotechnical projects, the use of water in this test is acceptable because it simulates the environment in which the soil will be used. However, many industrial waste disposal facilities will generate aggressive leachates and, as part of the ASTM procedure, the liquid limit should be tested using a simulated waste effluent. By comparing these two liquid limit values, the sensitivity of the soil vs liquid characteristics will be indicated. This procedure can reveal, at an early stage of site investigation, the general compatibility between the soil being considered as a liner and the specific waste. If the determination of the liquid limit using the waste effluent yields a drastic change in the limit compared to that using water, the permeability of the soil should be thoroughly studied with the particular waste effluent. On the other hand, if the limit using the two liquids is the same, the conclusion can be drawn that a limited number of permeability determinations using the waste effluent should suffice.

3.2.3.2 Compactibility

The practice of soil compaction is a routinely used procedure of site improvement. It is well known that, generally, the higher the density of a soil, the higher its strength, and thus the soil is better suited as a geotechnical material.

Soil compaction has the same beneficial effect on soil permeability provided all conditions are held constant, the higher the density of a soil, the lower its permeability. This relationship seems to be, however, more complex than the density/strength relationship, because upon densification "all conditions" cannot be held constant. In particular, soil fabric is altered and since soil flow characteristics are very sensitive to structural changes, the relationship between soil density and permeability is not a simple one.

Some of the interactions between several independent variables which affect the density-permeablity relationship are discussed in Chapter 5.

The fundamental aspects of soil compaction were established almost a half-century ago by R. R. Proctor (Burmister, 1964). Thus, it was found that any soil has a characteristic laboratory density/moisture relationship if compaction conditions are held constant. This relationship defines a unique density value (maximum density) and a corresponding moisture (optimum moisture content), which are essential parameters for design considerations.

It is well recognized that an increase of compactive energy increases the characteristic maximum density and decreases the optimum moisture value (Felt, 1965). Similarly, it was found that a time factor is involved in the compaction process. The longer the compactive effort is applied, the higher the density value, which is a logical consequence of the fact that volume reduction upon compaction is a progressive microfailure mechanism in which during load application the magnitude of average stress per bond increases continuously and stronger bonds become vulnerable to breakage.

The laboratory or field soil layer thickness, upon which the compactive effort is applied, is significant in terms of the overall bulk sample or site density. The smaller the layer thickness, the higher the density achieved. This fact is a result of stress distribution below the compactive implement.

As a general rule, the effect of soil mechanical composition on the shape and position of the moisture-density relationship is as follows:

a. The more granular and the better graded the soil, the higher the maximum density and, consequently, the lower the optimum moisture.

b. The finer the soil (the more clayey it is), the less defined the maximum density and the flatter the curve on the dry-of-optimum side. This is because the effect of equal increments of water added to a soil dry-of-optimum depends on the concentration of fines in the soil. The larger the proportion of fines, the smaller the moisture content of the clay unit when the same amount of water per unit of soil is added dry-of-optimum. Since the clay fraction is a binder of larger soil particles and since clay strength is related to its moisture content (effective stress concept in unsaturated soils), the more clay in the soil, the "drier" the clay fraction at the same soil moisture content and thus the more the bulk sample will resist densification.

Considerable effort was directed toward correlating field and laboratory compaction characteristics, particularly following the introduction of the modified AASHTO compaction test procedure (McDowell, 1946).

Uniformity of moisture content of the field soil that is to be compacted is important, particularly when light rollers are being used. Heavy rollers seem to be more effective in compacting soil in a field of variable moisture content (Burmister, 1964).

For reasons which will be explained in detail in Section 3.2.3.4, the compaction operation in the field has to be conducted at a moisture content as high as possible. However, when the compaction is performed in the field at a moisture content over the optimum, operation limitations restrict using heavy rollers; in this case, the desired density has to be achieved by increasing the number of passes over the compacting layer. Some experimental results have also shown that increasing the foot pressure used and decreasing the lift in the same proportion result in equally dense soils (Sowers and Gulliver, 1955).

In Chapter 5, we will discuss the methodology of designing a soil liner, indicating the laboratory information needed to formulate the design criteria. At this stage, we want to reiterate that most of the knowledge available in the soil mechanics literature on soil compaction is basically applicable for the situation when a waste impoundment soil liner is being prepared. However, the designer should be aware of the particularities of such a "hydraulic" structure, among which the character of the liquid that percolates through the liner is the most prominent. Another complicating factor is the complex relationship between soil permeability and density, even when water is the percolating liquid.

3.2.3.3 Volume changes

Volume changes that may occur following compaction of the soil liner should be estimated because a change in bulk density will result in a change in transport properties. If a soil is marginal in terms of its potential for generating a particular "as compacted" K value, and if it has a high swell/shrink tendency, it will likely be rejected as a liner candidate.

In general, volume changes have a detrimental effect upon soil permeability. However, there are conditions and circumstances when the effect may be beneficial, i.e. when a sealing of the soil occurs as a result of the high volume changes of the particular soil. Thus, volume change tendencies should be known because, if they alter the designed properties to the extent that an opening of the structure is generated, a progressive failure is initiated. Failure mechanism as it relates to swell and shrink is explained in Chapter 4.

If the moisture content of the soil element under consideration will change compared to the "as-compacted" state, then swelling or shrinking may occur provided the necessary conditions are present. According to Nayak and Christensen (1971), the following factors determine the intensity of volume change manifestation:

- Type and amount of clay mineral.
- Nature of pore liquid.
- Initial placement condition, e.g. structure and density.
- Stress history.
- Temperature.
- Volume change permitted during swelling pressure measurements.
- Shape, size, and thickness of the sample.
- Time.

In this section, we present a discussion on the first three of these factors since they are most significant when assessing the susceptibility to volume change of a soil liner retaining waste leachate.

The characteristics and concentration of the clay component have a dominating effect on volume change behavior to the extent that quite often we associate swelling and shrinking soils with the term "clay" soils. This is a consequence mainly of three characteristics of clay particles compared to larger silt and sand size particles:

1. Water adsorption and retention is a surface phenomenon. The greater the surface of the soil particles, the more water is retained. Thus, the higher the clay concentration in a sample, the greater the surface and the larger the amount of water associated with the unit mass of the soil sample.

2. Unlike bulkier soil particles, the clay particles are charged, usually carrying a negative charge. This results in a preferential retention in the immediate vicinity of the clay surface of cations which are hydrated in natural environments.

3. In the case of many widespread clay mineral species, e.g. members of the smectite group, the retention of water is not a surface phenomenon in the sense that water penetrates inside the particle. Thus, it is an imbibition mechanism which results in an association of water beyond and over the amount proportional to the clay external surface.

The nature and characteristics of the liquid interacting with the clay have a profound effect on specific adsorption. This has long been known for the condition when water is the liquid phase. The chemical composition of the solution and its total electrolyte concentration perturb the configuration of the "exchangeable cations" and thus control the interlayer volume for liquid penetration. The swell and shrink characteristics of the clay are highly controlled by the composition of the liquid.

The condition in which the liquid phase contacting the soil is not water but a different organic compound (less investigated because it does not constitute a natural environment) is of great significance for soil liners. In Chapter 4, examples are given to reveal the drastic effect some organic compounds have upon volume change characteristics of different clays. Some organics interact with clays so specifically that they represent standard reagents for clay mineral identification. Thus, solvation with glycerol of a Mg-saturated clay sample containing montmorillonite, vermiculite, and chlorite, with an original basal (001) diffraction spacing of 1.45 nm, allows the identification of montmorillonite because this is the only component which increases its treated basal spacing to exactly 1.8 nm.

Basic information on liquid chemistry/clay swell interaction can be found in the two monographs on clays by Grim (1962, 1968) and in the two excellent volumes on soil behavior written by Yong and Warkentin (1975) and Mitchell (1976).

The third significant factor which has a considerable impact on volume change behavior of soils containing an appreciable amount of clay (e.g. over 20%) is the sample preparation or, for the field condition, the placement and compaction characteristics. Thus, the structural characteristics of the clay generated as a result of a particular compaction procedure are very significant in terms of subsequent volume change behavior. If two samples of the same soil are compacted at the same moisture content using two different compacting procedures (e.g. static vs kneading), it is likely that two different structures will be generated. This should be reflected by the pore-water pressures measured on the as-compacted specimens. Normally, this value should be smaller for the statically-compacted sample (larger negative value). This means that the statically-compacted specimen should behave as being drier and thus should subsequently absorb more water, if available, and swell more. As a general rule, however, the differences in structure generated in the dry-side-of-optimum, due to the different methods of compaction, have a minimal effect upon shrink/swell characteristics. The same is not true on the wet side; the statically compacted soil (with a more flocculated structure) swells more than the sample compacted with a kneading compactor. Day (1955) showed a decrease in soil suction upon shear when, presumably, the soil particles were in a less flocculated state in comparison to the situation "at rest", when the particles tended to have a more flocculated arrangement.

A revealing graphic representation of the tendency of compacted soil to swell was presented by Holtz and Gibbs (1956) and is reproduced in Figure 3-2 These authors were able to show that (Seed et al, 1962):

a. As a general trend, the lower the moisture content and the higher the density, the higher the swell potential.

b. An increase in molding water content at a given density causes a decrease in swelling pressure and swell.

c. An increase in density at low moisture content causes an increase in swell. An increase in density at high moisture content does not alter drastically the swell characteristics.

Graphs like the one presented in Figure 3-2 are very useful. However, they refer to the bulk swell behavior of the sample. When the strength or settlement characteristics of a soil are of concern, information similar to that presented in Figure 3-2 is useful, unless the compacted structure is metastable. However, for assessing the effect of swell on liquid transmission characteristics, the internal swell behavior is particularly important, even when the bulk sample does not change its volume. Volume change as a failure mechanism will be discussed in Chapter 4.

3.2.3.4 Permeability

Soil permeability, K, is the rate of movement of a unit volume of fluid per unit cross-sectional area perpendicular to the flow direction normalized per unit gradient. In geotechnical work, when water is the fluid under consideration, the permeability is specifically referred to as hydraulic conductivity.

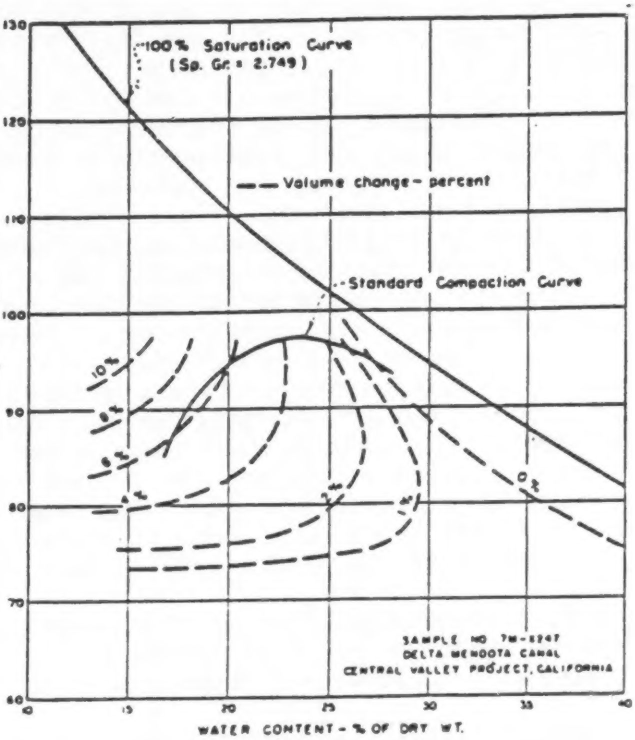

Figure 3-2. Isoswell lines on moisture-density graph; expansive clays under extremely dry and dense conditions (Holtz and Gibbs, 1956).

Soil permeability is a measure of the ability of the soil to transmit a particular liquid and is one of the most important geotechnical characteristics, particularly in the case of clay soils. The rate of consolidation and settlement and, thus, the stability of an earth structure depends on soil permeability. In the case of a heterogeneous soil body, the rate of water movement in one part of the body may or may not change the pore-water pressure in another part of the body and, thus, again the stability of the earth structure depends on soil permeability. Finally, when a water-retaining earth structure is constructed, the amount of water lost through seepage is important; in this case, the hydraulic conductivity has a direct significance.

Soil permeability is determined using Darcy's relationship:

$$J = K \cdot \nabla H$$

where:

J is the volume of liquid passing through a unit cross-sectional area of soil per unit time, and

∇H is the hydraulic gradient, i.e. the rate of change of hydraulic head in the direction of flow.

When H is expressed as "weight hydraulic potential" (units of length, L) and J as volume divided by unit area times unit time (units of rate, LT^{-1}), the permeability is expressed in the c.g.s. system as cm s^{-1}.

Darcy's law is a useful relationship which has been widely used to determine K. Its simplicity reflects a well-proven fact, namely, that among all factors determining the flux, J, the magnitude of the gradient is so overwhelming in its significance that it masks the importance of other factors.

The main feature of this relationship, the linearity between gradient and flux, i.e. the constancy of K, is well documented for most soils. The validity of Darcy's Law has been questioned for some clay soils. Thus, in highly compacted and very fine clays, the physical properties of a large proportion of the pore liquid may be altered due to the proximity between the liquid and the soil matrix. Keeping the gradient constant but increasing the pore-water pressure while the soil element is confined (constant void ratio), relaxes the soil structure and increases the proportion of water affected by the matrix proximity, and thus its average viscosity. The result is a soil structure displaying a lower hydraulic conductivity.

A more drastic effect in changing the K value is obtained with some clay soils when the gradient is increased to the extent that it induces total separation of clay particles and causes migration of colloidal clay, which subsequently plugs some of the pores.

In spite of its limitations, Darcy's Law is still the main relation used to describe the water flow in soils, particularly for rigid soil structures, i.e. those which are neither affected by the magnitude of the pore-water pressure and the gradient, nor by osmotic and swelling effects. In qualitative terms, this relation will always be accepted, since the larger the hydraulic gradient, the larger the resulting flux.

Because K depends on properties of both components, soil and liquid, the intrinsic soil/flow properties can be identified by taking into account the viscosity and density characteristics of the liquid. The resulting parameter was called "intrinsic permeability" and the corresponding units in the c.g.s. system are cm^2. In this case, the liquid viscosity normalizes the resistance to flow due to the liquid cohesiveness, while the liquid density normalizes the effect of gravity on liquid flow. In principle, the use of intrinsic permeability permits comparison of K values of several soil specimens of the same soil, when permeated by different fluids.

In the case of lined waste disposal facilities, the soil liner may be contacted by liquids of exotic chemical compositions. In this case, the kinematic viscosity correction which is operated on K to produce the intrinsic permeability, is a minor improvement.

The primary goal of constructing a soil blanket of low permeability is carried out in the field by soil compaction. Through this operation a dense soil material is obtained with a lower void ratio. According to both Taylor-Poisseuille and Kozeny-Carman relationships (Lambe and Whitman, 1979), K is proportional to e^3 $(1+e)^{-1}$ where e is the void ratio. This relationship has not been quantitatively verified for fine soils.

The reduction of the void ratio upon compaction promotes two changes in the soil: a decrease of the effective area available for flow (effective pore area being measured perpendicular to the flow direction), and a decrease of the median pore size value. The latter decrease is important because, according to the capillary model, the flux (LT^{-1}) is proportional to the second power of the radius. Thus, a reduction in the void ratio should result in a considerable reduction of permeability, K.

An important consequence of the K-e function is that, as soils are particulate media and K is always measured on specimens for which the sample size is much greater than average particle size, K will always be positive since the condition e=0 contradicts the definition of a soil as a porous medium. Consequently, truly impermeable soils (K=0) do not exist.

Most undisturbed soils have permeabilities to water in the range of 10^{-7} cm s^{-1} to 10^{-3} cm s^{-1}. Intrinsic soil characteristics as well as naturally occurring environmental conditions play a tremendous role in the resulting broad range of permeabilities encountered in nature. If one looks over the whole range of permeability values of undisturbed soil, the particle size characteristics seem to be the most relevant; soils with more than 25-30% clay size particles are concentrated in the lower range of permeabilities, i.e. 10^{-7} cm s^{-1} to 10^{-5} cm s^{-1}. If, however, one tries to correlate K with the percentage of clay size particles over this latter narrow range of permeabilities, the relation between particle size and permeability becomes less significant, i.e. other factors become relatively more significant in their effect upon flow properties. The types of clay minerals present in the clay fraction and the particle size distribution in the less than 2 μm fraction play a very important role. The interlayer chemistry of the crystal-unit, the susceptibility of the particles to disperse or flocculate upon hydration and/or mechanical remolding, and the average size of a typical soil aggregate are factors that effect profoundly soil-water flow characteristics; they can alter the K value by as much as two orders of magnitude for otherwise apparently similar soils. Since this can make the difference between using or not using a particular soil as a liner, the site designer should obtain pertinent information regarding physicochemical and mineralogical properties of the clay in the soil.

The physicochemical behavior of a clay soil has such an overwhelming effect upon soil permeability because of the dependence of soil clay structure on physicochemical properties and the effect of the structure on permeability. If a soil clay fraction has a fixed structure, totally insensitive to changes in hydration conditions and the way in which stresses are applied, then the K vs w (water content) function would be a mirror image of the γ (density) vs w function with the lowest permeability corresponding to the maximum density, on the γ vs w graph. Physicochemical factors have a drastic effect on clays, particularly in the case of montmorillonite clays; they have a very sensitive structure and the permeability of a montmorillonite soil is far from being a simple function of density.

Lambe (1958) showed that the permeability of a clay compacted dry-of-optimum is much greater than that compacted on the wet side of the optimum. He also concluded that the higher the compactive effort, the smaller the difference between the ranges of permeabilities obtained on both sides of the optimum. Clay compacted dry-of-optimum was found to have an "open", flocculated structure, while the wet-of-optimum clay tends to have a dispersed structure. This effect determines the flow properties to such an extent that little is left of the general belief that soil permeability and density are inversely related. Lambe (1958) also noted that on the dry-of-optimum side, a threshold pressure appears to exist beyond which the clay structure tends to reproduce the structure of the "wet"-clay, i.e. to orient its particles parallel to a preferred plane.

Some of these conclusions were carefully investigated in the 1960s by Mitchell, et al (1965). In carrying out the investigation on a silty-clay for which some of its mechanical properties were well documented, Seed and Chan (1959) Mitchell et al (1965) confirmed the above conclusions and simultaneously revealed new effects. Thus, combining different compactive efforts with different moisture contents to produce a unique, high density soil (108 lb ft^{-3} or 1.732 g cm^{-3}), the permeability showed a slight increase with the water content, on the dry side of optimum.

The effects of the compaction procedure were also investigated. When samples were compacted by kneading compaction using the same compactive effort at different combinations of w and γ, the slight effect of K increase with density and moisture content in the dry-of-optimum range was still present; but when the experiment was repeated with a different soil (over a more narrow range of moisture content) the effect was not present, i.e. samples prepared dry-of-optimum indicated a "normal" drop of permeability with an increase in density.

Mitchell et al (1965) indicated that, when samples are compacted at a moisture content below the optimum moisture, the K vs w function depends on so many factors that, if precise information is needed, testing of the soil simulating the field condition is the only alternative. Further increase in moisture content beyond the optimum moisture resulted in a tremendous drop in K-value. Furthermore, the results presented by Mitchell et al (1965) indicate that the choice and use of a particular compacting effort is significant to the K-value, particularly on the wet side of optimum. Using a very high moisture content and compacting their silty-clay soil specimens using a kneading compactor at the same void ratio, but using different compactive efforts, the authors obtained a large range of K-values (over two orders of magnitude). The conclusion is that, by compacting the soil at a very high moisture content, the permeability can be significantly decreased by structural arrangements of soil (clay) particles rather than diminishing the total void space of the soil.

The picture presented above refers to laboratory soil specimens compacted with a kneading compactor, which better resembles the compaction of soils in the field compared to static compaction (Lambe and Whitman, 1979). It has been conclusively shown that particle preferential orientation and consequently reduction of permeability upon compaction is more prominent in samples which are compacted using a kneading compactor rather than impact, vibratory, or static compaction (Seed and Chan, 1959; Mitchell et al, 1965).

Mitchell (1956) pointed out that clays, and presumably clay soils, are quite different in their behavior upon remolding. In general, clay deposits which are formed in marine or brackish environments are quite efficiently remolded, i.e. a preferred orientation upon remolding can be achieved; this conclusion seems to be particularly true for clays which have been precompressed in nature at very low stresses, e.g. the Scandinavian sensitive clays. Clay deposits which have been sedimented in fresh waters and have been highly precompressed, e.g. the Texas and New Orleans clays investigated by Mitchell, could not be efficiently remolded since they already had an oriented structure in their undisturbed state. Consequently, in establishing the technology to be used for producing a soil liner, the designer should have information on both the natural preconsolidation pressure of the soil and the conditions at formation or deposition of the soil.

The sensitivity of a soil is the ratio of the strength of the undisturbed soil to that of the soil after remolding. Seed and Chan (1959) have indicated that a simple test for revealing a sensitive structure is to compare the undrained stress-strain characteristics of an undisturbed soil sample with those of a sample remolded wet-of-optimum (Mitchell, 1964). Because, in the case of a soil liner, the permeability is the property to be considered and since soil flow properties are at least as much structure sensitive as strength properties are, the permeability rather than the strength should be determined on undisturbed and remolded samples. Static and kneading compaction procedures should be used in parallel to evaluate the effect of void ratio and to identify the eventual effect a particular structure might have on permeabilty.

The following conclusions should be considered when clay soils are compacted to produce the lowest possible permeability:

a. The lowest permeabilities correspond, as a general rule, to the condition when the soil is compacted wet-of-optimum moisture.

b. The sensitivity of a soil structure unit is ascertained by increasing the available water and the available compactive effort and measuring the decrease in permeability. The testing program should should reveal the relative significance of these two factors and lead to the optimization of field compaction; the investigation should identify the relative effects upon permeability of structural vs density changes when the soil is being compacted.

c. Compactive implements which promote shear deformation of soil will generate a better oriented structure and consequently help obtain a soil blanket with a low permeability.

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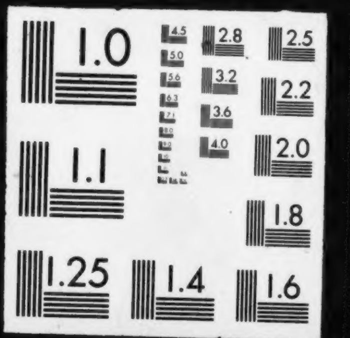
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1.25
1.4
1.6

d. The higher the moisture content during compaction, the more critically important is the density obtained, e.g. a small decrease in density (1%) may result in a permeability increase of one order of magnitude.

The subject of soil permeability will be discussed further in Chapter 4 and 5.

Chapter 4 will present more detailed information on the interaction between liquid chemistry, clay physicochemical and mineralogical properties, and permeability. The discussion will be made in the context of soil liner failure, i.e. an increase in permeability beyond the designed value.

Chapter 5 will present the information required to design a soil liner, the use of this information, and the permeability values to be reached in different circumstances.

3.3 ADMIXED LINING MATERIALS

3.3.1 Introduction

A variety of admixed or formed-in-place liners have been successfully used in the impoundment and conveyance of water. These linings include asphalt concrete, soil cement, and soil asphalt, all of which are hard-surface materials. The amount of experience in the use of some of the admixes in the lining of sanitary landfills and the lining of impoundments of brine is limited. Materials of this type have undergone exposure testing in contact with municipal solid waste leachate (Haxo and White, 1976; Haxo et al, 1982) in one EPA research project, and are undergoing limited exposure testing in a second project with hazardous wastes (Haxo et al, 1977). In this section the following types of admixes are discussed: hydraulic asphalt concrete, soil cement, and soil asphalt. Bentonite clay is also discussed in this section, as it is usually a processed product which is spread and mixed into on-site soil, and thus can be considered an admixed material.

3.3.2 Hydraulic Asphalt Concrete (HAC)

Hydraulic asphalt concretes, used as liners for hydraulic structures and waste disposal facilities, are controlled hot mixtures of asphalt cement and high quality mineral aggregate, compacted into a uniform dense mass. They are similar to highway paving asphalt concrete but have a higher percentage of mineral fillers and a higher percentage (usually 6.5 to 9.5) of asphalt cement. The asphalt used in hydraulic asphalt cement is usually a hard grade, such as 40-50 or 60-70 penetration grade. These harder asphalts are better suited as liners than softer paving asphalt (Asphalt Institute, 1976).

A major factor in the design of a hydraulic asphalt mix for use as a liner to confine wastes is the selection of an aggregate that is compatible with the waste. For example, aggregate containing carbonates must be avoided in HAC liners for acidic wastes.

Hydraulic asphalt concrete can be compacted to have a permeability coefficient less than 1 x 10^{-7} cm s^{-1}. It is resistant to the destructive wave action of water, light vehicular traffic, and effects of weather extremes (temperature). Such asphalt concrete is stable on side slopes, resisting slip and creep, and retains enough flexibility to conform to slight deformations of the subgrade and avoid rupture from low level seismic activity. Asphalt concrete liners may be placed with conventional paving equipment and compacted to the required thickness (Asphalt Institute, 1966).

Styron and Fry (1979) used 11 percent asphalt in a two-inch asphalt concrete liner to obtain the necessary permeability. Haxo et al (1982) used a nine percent asphalt concrete, but after one year of exposure to leachate from a simulated landfill, determined that due to potential inhomogeneities in the admixed materials, resulting from inadequate mixing or compaction, a liner thickness greater than four inches may be necessary to contain wastes (Table 3-3). The HAC liner examined after 56 months of exposure was in good condition; properties had changed very little since the first specimen was examined at one year of exposure. A study by Southern California Edison showed that an optimal compacted thickness, for a pond holding primarily water, was two layers of two inches each for a total thickness of four inches (Hinkle, 1976).

The quality of the finished liner depends on the compaction during placement (Bureau of Reclamation, 1963, p 40). The liner should be compacted to at least 97% of the density obtained by the Marshall Method (Asphalt Institute, 1976) or less than 4% voids (Asphalt Institute, 1981). Hinkle (1976) found that a voids content less than 2.5% produced a permeability of less than 0.001 ft/yr (1 x 10^{-9} cm s^{-1}), as shown in Table 3-4. Samples containing 8.5% asphalt at 97% compaction, in a pressurized permeameter, showed no observable flow (Hinkle, 1976).

Before placement of the liner, the subgrade should be properly prepared. It should not have side slopes greater than 2:1 and preferably no greater than 3:1 (Asphalt Institute, 1966). The soil should be treated with a soil sterilant to prevent puncture of the liner by weeds and roots (Asphalt Institute, 1966). Mixtures of sodium chlorate and borates are examples of such soil sterilants (Bureau of Reclamation, 1963).

Asphalt has been used for centuries as a water resistant material. More recent usage has shown that asphalt materials also are resistant to acids, bases, inorganic salts (to a 30% concentration) and to some organic compounds found in industrial wastes (Asphalt Institute, 1976). Asphalts are generally not resistant to organic solvents and chemicals, particularly hydrocarbons in which they are partially or wholly soluble. Consequently, asphalts are not effective liners for disposal sites containing petroleum derived wastes or petroleum solvating compounds such as oils, fats, aromatic solvents, or hydrogen halide vapors. Asphalt does show good resistance to inorganic chemicals and low permeability to corrosive gases such as hydrogen sulfide and sulfur dioxide.

3.3.3 Soil Cement

Soil cement is a compacted mixture of portland cement, water, and selected in-place soils. The result is a low strength portland cement concrete with greater stability than natural soil. The permeability of this mixture varies with the type of soil; a more granular soil produces a more permeable soil cement. A fine-grained soil produces a soil cement with a permeability coefficient of about 10^{-6} cm s^{-1} (Stewart, 1978). To date, there have been few studies performed to design a soil cement with very low permeabilities (less than 10^{-8} cm s^{-1}), as opposed to mixes designed for high compressive strength. To reduce permeability of soil cement, coatings such as epoxy asphalt and epoxy coal-tar have been used.

Any soil, except organic soil, with less than 50% silt and clay is suitable for soil cement. However, a well-graded soil with a maximum size of 0.75 inch and a maximum silt and clay content of 35% is preferable (Bureau of Reclamation, 1963). A high clay content impairs the ability to form a homogeneous cemented material thus reducing the efficiency of producing an impermeable layer. Three criteria must be considered for soil cement liners: cement content, moisture content, and the degree of compaction. The optimum moisture and cement contents are determined by laboratory testing. The soil optimum moisture is that which results in maximum density of the compacted cement. Laboratory samples should be tested in wet-dry and freeze-thaw cycle tests (ASTM D559 and ASTM D560) to determine the optimum cement content.

The aging and weathering characteristics of soil cements are good, especially those associated with wet-dry, freeze-thaw cycles. Some degradation has been noted when this substance is exposed to highly acidic environments (Stewart, 1978), but soil cements can resist moderate amounts of alkali, organic matter, and inorganic salts. One of the main deficiencies of soil cement as a liner material is its tendency to crack and shrink on drying.

3.3.4 Soil Asphalt

Soil asphalt is a mixture of available on-site soil, usually low plasticity, and liquid asphalt. A silty, gravelly soil with 10-25% silty fines is the preferred soil type. The permeability of soil asphalt after compaction varies with the percent compaction and the percent asphalt. A high void content (3-10%) soil asphalt has a measurable permeability. Soil asphalts containing cutback asphalt are not recommended as lining materials. Soil asphalt made with asphalt emulsion is not sufficiently impermeable and requires a waterproof seal such as a hydrocarbon resistant or bituminous seal (Asphalt Institute, 1976).

3.3.5 Bentonite-Soil Mixtures

3.3.5.1 Types of bentonite

Bentonite is a colloidal clay composed chiefly of the clay mineral montmorillonite which was briefly discussed separately in the soils part of this chapter (Section 3.2.2.1) There are two major varieties of bentonite: (1)

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TABLE 3-3. COMPOSITION AND PROPERTIES OF ADMIXED AND ASPHALT MEMBRANE LINERS - UNEXPOSED AND AFTER EXPOSURE

	Asphalt concrete	Hydraulic asphalt concrete	Soil cement	Soil asphalt
Basic composition	7.1 parts 60-70 pen paving asphalt, 100 parts aggregate	9.0 parts 60-70 pen paving asphalt, 100 parts aggregate	95 parts soil, 5 parts Kaolin clay, 10 parts type 5 cement, 8.8 parts water	7.0 parts SC-800 liquid asphalt, 100 parts aggregate
Thickness, in.	2.2	2.4	4.5	4
Tests of aggregates				
Particle size distribution of aggregate				
Passing 4 mesh, %	90.7	89.4	88.9	79.2
" 8 ", %	61.0	67.1	70.8	55.8
" 16 ", %	45.1	50.9	53.7	39.9
" 30 ", %	30.1	33.7	38.8	27.3
" 50 ", %	19.4	21.5	29.2	18.5
" 100 ", %	11.2	12.4	20.8	13.4
" 200 ", %	6.6	7.2	15.0	11.4
Soil tests				
Sand equivalent	...	...	27	31
Liquid limit	...	...	17.6	17.0
Plastic limit	...	...	Non-plastic	Non-plastic
Plasticity index	...	...	Non-plastic	Non-plastic
Asphalt tests				
Penetration at 25°C/100 g/5 sec				
Before mixing	68	68	...	...
Extracted from core	44	62	...	...
Microductility at 25°C, mm	40	76	...	7
Properties of unexposed samples				
Density, g/cm^3	2.387	2.416	2.169 (dry)^a	2.228
lb/ft^3	149.0	150.8	135.4 (dry)^a	139.1
Voids ratio (vol. voids/vol. solids), %	6.4	2.9	...	10.4
Water swell, mil	1	0	0	17
Coefficient of permeability, cm sec^{-1}	1.2×10^{-8}	3.3×10^{-9}	1.5×10^{-6a}	1.7×10^{-3}
Compressive strength				
Initial, psi	2805	2710	1910^a	1220
After 24 h immersion in water^b, psi	2230	2330	1320^a	185
Retention of strength after immersion, %	80	86	69^a	15

See footnotes at end of table.

TABLE 3-3 (Continued)

	Asphalt concrete	Hydraulic asphalt concrete	Soil cement	Soil asphalt
Basic composition	7.1 parts 60-70 pen paving asphalt, 100 parts per aggregate	9.0 parts 60-70 pen paving asphalt, 100 parts per aggregate	95 parts soil, 5 parts Kaolin clay, 10 parts type 5 cement, 8.8 parts water	7.0 parts SC-800 liquid asphalt, 100 parts aggregate
Properties after 12 months of exposure^c				
Density, as received, g/cm^3	2.430	2.400	...	2.161
Density, dry, g/cm^3	2.406	2.309	...	1.973
Voids ratio as received, %	3.2	1.5	...	15.2
Voids ratio, dry, % (number of samples)	4.2 (3)	1.9 (4)	...	26.1 (3)
Water content, g water per 100 g dry solids (number of samples)	1.00 (3)	0.45 (4)	...	9.6 (3)
Water soluble solids extracted, % (number of samples)	0.008 (1)	<0.01 (2)	...	0.14 (3)
Compressive strength, psi	423	349	1188	15
Percent of original	15	13	62	1.2
Coefficient of permeability, cm sec^{-1} (two samples)	7.4×10^{-7} 9.3×10^{-9}	3.5×10^{-9} $<3 \times 10^{-10}$	1.5×10^{-8} (T)^d 4.0×10^{-7} (B)	1.3×10^{-8} 2.8×10^{-8}
Properties after 56 months of exposure^c				
Density, as received, g/cm^3	2.542	2.471	...	2.307
Density, dry, g/cm^3	2.417	2.385	...	2.019
Voids ratio, as received, %	4.3	4.6	...	5.0
Voids ratio, dry, % (number of samples)	5.3 (2)	3.6 (2)	...	14.3
Water content, g water per 100 g dry solids	1.06	0.96	...	6.51
Water soluble solids extracted, % (number of samples)	0.016 (2)	0.008 (2)	...	0.10 (2)
Compressive strength, psi (number of samples)	258 (2)	172 (2)	1182 (4)	26 (2)
Percent of original	9	6	62	2
Coefficient of permeability, cm sec^{-1}	$<10^{-7}$	$<10^{-9}$	1.2×10^{-5} (T)^d 2.7×10^{-5} (B) 4.3×10^{-7} (T) 1.2×10^{-5} (B)	8.6×10^{-8} (T)^d 2.7×10^{-7} (B)

[a] Measured on specimen molded according to ASTM D 558. Wet density, 2.345 g cm^{-3} (146.4 lb ft^{-3}).

[b] Asphalt concrete and hydraulic asphalt concrete immersed in water at 60°C; soil cement and soil asphalt immersed at room temperature.

[c] Measured on 2-inch cores cut from liner specimens.

[d] Data for top (T) and bottom (B) of core are shown (Vallerga and Hicks, 1968).

TABLE 3-4. PERMEABILITY OF ASPHALT CONCRETE TO WATER

Asphalt, %	Compaction[a], %	Voids, %	Specific gravity	Unit weight	Maximum specific gravity	Permeability constant, millidarcys	Coefficient of permeability	
							cm/sec	ft/yr
7.5	99.2	2.8	2.248	140.3	2.313	7.6×10^{-7}	7.9×10^{-7}	0.82
7.5	98.0	3.9	2.223	138.7	2.313	1.6×10^{-7}	1.7×10^{-7}	0.18
7.5	93.8	8.0	2.128	132.8	2.313	1.05×10^{-4}	1.09×10^{-4}	112
7.5	91.4	10.4	2.072	129.1	2.313	1.53×10^{-3}	1.58×10^{-3}	1630
7.75	96.0	6.9	2.147	134.0	2.306	1.97×10^{-6}	2.04×10^{-6}	2.1
7.75	99.0	2.9	2.240	139.8	2.306	9.7×10^{-7}	1.0×10^{-6}	1.0
8.0	93.2	8.0	2.115	132.0	2.299	1.3×10^{-4}	1.31×10^{-4}	136
8.0	93.0	8.4	2.107	131.5	2.299	1.3×10^{-3}	1.3×10^{-3}	1340
8.0	98.7	2.6	2.240	139.8	2.299	$<1.9 \times 10^{-9}$	$<2 \times 10^{-9}$	<0.002
8.5	90.6	9.5	2.067	129.0	2.285	3.0×10^{-7}	3.1×10^{-7}	0.32
8.5	94.4	6.0	2.147	134.0	2.285	5.2×10^{-8}	5.4×10^{-8}	0.056
8.5	94.0	6.2	2.144	133.8	2.285	4.3×10^{-5}	4.4×10^{-5}	46
8.5	96.0	4.2	2.189	136.6	2.285	1.3×10^{-5}	1.4×10^{-5}	14
8.5	96.0	4.2	2.189	136.6	2.285	8.2×10^{-6}	8.48×10^{-6}	8.8
8.5	97.0	3.2	2.313	138.0	2.285	$<4.8 \times 10^{-9}$	$<5 \times 10^{-9}$	<0.005
8.5	98.0	2.1	2.236	139.5	2.285	$<3.8 \times 10^{-9}$	$<4 \times 10^{-9}$	<0.004
8.5	98.0	2.6	2.224	138.8	2.285	$<5.5 \times 10^{-10}$	$<5.7 \times 10^{-10}$	<0.0005[c]
8.75	99.0	2.3	2.226	138.9	2.279	$<1.6 \times 10^{-9}$	$<1.88 \times 10^{-9}$	<0.0016[b]
8.75	99.8	1.7	2.240	139.8	2.279	$<9.6 \times 10^{-10}$	$<9.28 \times 10^{-10}$	<0.0009[b]
8.75	99.5	2.0	2.232	139.3	2.279	$<8.0 \times 10^{-10}$	$<7.79 \times 10^{-10}$	<0.0007[b]
8.75	98.0	3.6	2.197	137.1	2.279	$<1.2 \times 10^{-9}$	$<1.21 \times 10^{-9}$	<0.001[b]

Source: Hinkle, 1976.

[a] Based upon 35 blows Marshall = 100%.

[b] Samples still on permeability apparatus at time of Hinkle's publication.

sodium bentonite, which has a high swelling capacity in water, and (2) calcium bentonite which has a negligible swelling capacity. Because of its high swelling capacity, sodium bentonite is used as a sealant or a lining material for water storage and conveyance. Polymer modifications of bentonite have been developed which have improved resistance to saline water.

Bentonite is commercially available in bags or in bulk as a fine powder or as granules. When used as a lining material, it is either applied directly, or mixed into sand or the top layer of soil and compacted. In either case, the layer containing bentonite is generally covered with a protective soil cover. Slurry trenches, filled with soil-bentonite slurry, are used to control lateral movement of water or liquid wastes. Compacted soil-bentonite or sand bentonite liners are usually 4 to 6 inches thick. A limited exposure test of a compacted sand-polymer modified-bentonite mixture is included in an EPA test program (Haxo et al, 1977).

3.3.5.2 Methods for evaluating bentonite mixtures

Bentonite content, moisture content and degree of compaction are the principal factors which determine the initial permeability of a soil-bentonite or sand-bentonite liner. Permeability over a long-term period of exposure is affected by ion exchange between the bentonite and components of the soil or the waste being impounded, or by absorption of organic components of the waste. Exchange of the sodium ions for calcium or aluminum, for example, converts the sodium bentonite to a lower-swelling material, less effective as a sealant than native clays. High concentrations of sodium in the water also inhibit swelling, due to "ionic crowding" (Hughes, 1977). Initial saturation of the bentonite with uncontaminated water minimizes the above effects, but the improvement may not be permanent.

Tests of effectivness of bentonite liners for containing wastes are necessarily very long-term, as short-term tests do not allow sufficient time for displacement of the pore water by waste. According to Hughes (1977), a pore volume displacement (PVD) of 2.0 is insufficent for definitive analysis of the contaminant-resistant capability of a bentonite, and he suggests that a PVD of 20 to 50 should be used.

3.4. FLEXIBLE POLYMERIC MEMBRANES

3.4.1 Introduction

Prefabricated liners based upon sheeting of polymeric materials are of particular interest for the lining of waste storage and disposal impoundments. As a group, these materials exhibit extremely low permeability. They have found substantial use in water impoundments in reservoirs and are being used in the lining of sanitary landfills and various waste disposal facilities.

Polymeric membrane liner technology is relatively new, particularly with its application to waste containment, and a wide variety of such liner materials are being manufactured and marketed. These materials vary considerably in physical and chemical properties, methods of installation, costs and interaction with various wastes. Not only are there variations in the polymers used, but there also is considerable variation in the lining materials of a given polymer type due to compounding, construction, and manufacturing differences among the producers.

In this section, the flexible membrane lining industry, the various polymeric materials, the testing, the seaming, and the liner construction and methods of manufacture are described and discussed.

3.4.2 Description of the Polymeric Liner Industry

Basically, the polymeric liner industry is composed of four major segments:

- Raw materials producers
- Manufacturers of sheeting or roll goods
- Fabricators of prefabricated panels
- Installers or construction contractors.

The relationship of these segments is illustrated further in Figure 3-3. A given company in the industry can perform two or more of these functions, e.g. a sheeting manufacturer might also fabricate and install; however, that is not the usual case. Another important factor is that of the design of the disposal site and the selection of the lining. This function is usually performed by engineering and consulting firms and at times by fabricators and installers.

Current representative lists of polymer producers, liner manufacturers, fabricators, and installers are included in Appendix II. The various segments of the industry are discussed in the following sections.

3.4.2.1 Raw materials production

The membrane or finished sheeting is made from one or more raw polymers combined with a variety of compounding ingredients, such as carbon black, pigments, fillers, plasticizers, processing aids, crosslinking chemicals, antidegradants and biocides. Table 3-5 presents such a list of polymers by generic name, their trade names or other common identification, and their respective producers.

The polymer producers normally supply technical service to reputable sheeting manufacturers, presenting recommended formulations, and manufacturing procedures. Some of the polymer producers conduct random monitoring of the sheet manufacturers to protect their polymer, but such quality control is growing more difficult to achieve because of the rapid growth of the industry. The individual polymers are discussed in Section 3.4.3.

3.4.2.2 Preparation of liner compounds and manufacture of sheeting

The final selection of compounding ingredients for each of the polymers is the responsibility of the sheeting manufacturer. The expertise employed in formulating, mixing, and forming sheets will control the properties of the finished liner. The polymer and its required compounding ingredients are

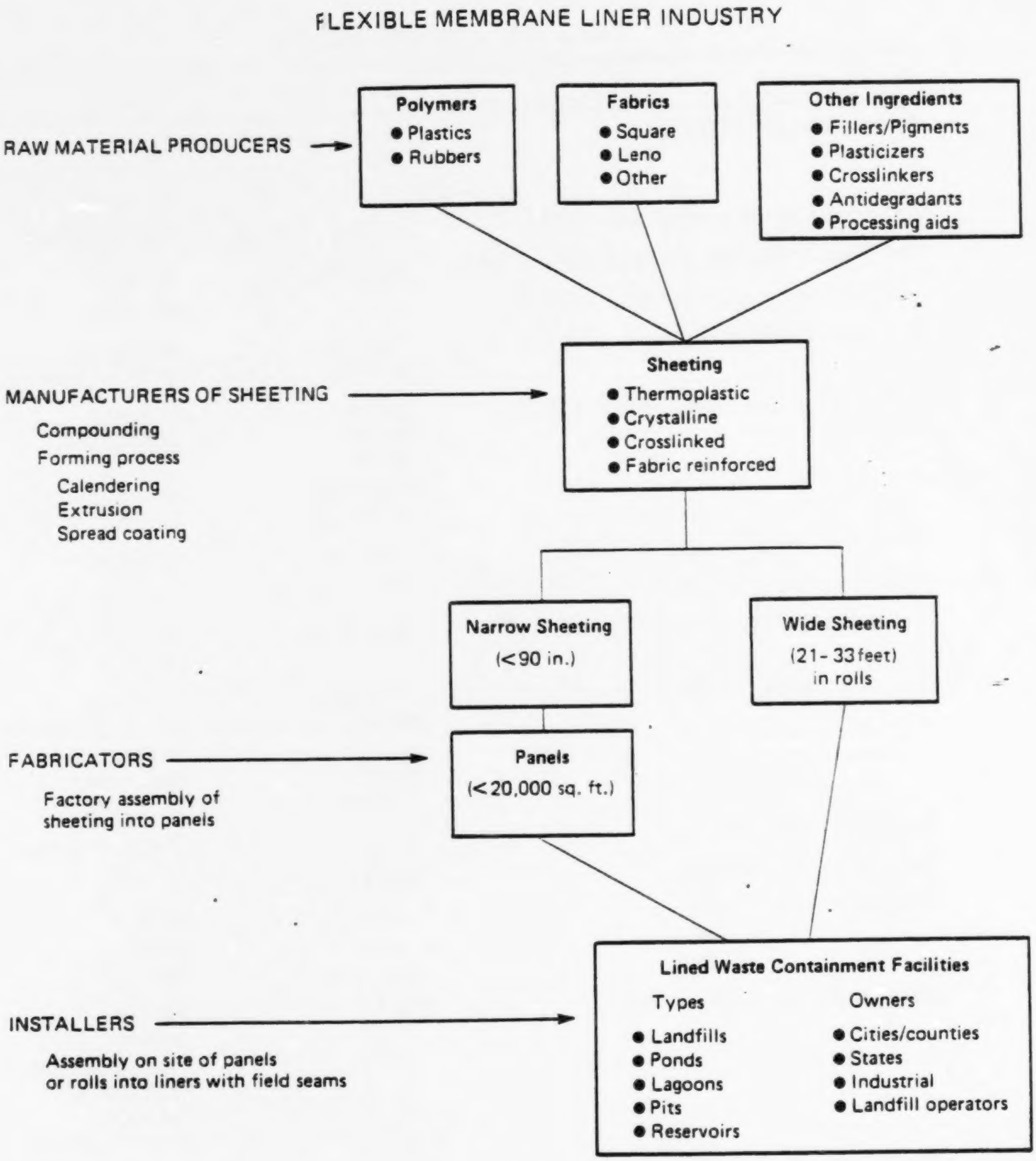
FLEXIBLE MEMBRANE LINER INDUSTRY
RAW MATERIAL PRODUCERS
Polymers
● Plastics
● Rubbers
Fabrics
● Square
● Leno
● Other
Other Ingredients
● Fillers/Pigments
● Plasticizers
● Crosslinkers
● Antidegradants
● Processing aids
MANUFACTURERS OF SHEETING
Compounding
Forming process
Calendering
Extrusion
Spread coating
Sheeting
● Thermoplastic
● Crystalline
● Crosslinked
● Fabric reinforced
Narrow Sheeting
(<90 in.)
Wide Sheeting
(21-33 feet)
in rolls
FABRICATORS
Factory assembly of sheeting into panels
Panels
(<20,000 sq. ft.)
INSTALLERS
Assembly on site of panels or rolls into liners with field seams
Lined Waste Containment Facilities
Types
● Landfills
● Ponds
● Lagoons
● Pits
● Reservoirs
Owners
● Cities/counties
● States
● Industrial
● Landfill operators

Figure 3-3. Basic structure of the polymeric membrane liner industry from raw material producers to liner installers. A representative list of organizations and personnel in the individual segments of the industry is presented in Appendix II.

TABLE 3-5. POLYMER PRODUCERS

Polymer	Trade Name	Company
Butyl rubber (IIR)	Butyl rubber[a]	Exxon Columbian Carbon Polysar
Chlorinated polyethylene (CPE)	CPE[a]	Dow Chemical
Chlorosulfonated polyethylene (CSPE)	Hypalon	Du Pont
Elasticized polyolefin	...	Du Pont
Epichlorohydrin rubbers (CO and ECO)	Herclor Hydrin	Hercules B. F. Goodrich
Ethylene propylene rubber (EPDM)	Epcar Epsyn Nordel Royalene Vistalon	Polysar Copolymer DuPont Uniroyal Exxon
Ethylene vinyl acetate (EVA)	Elvaloy	Du Pont
Fluorocarbon polymers	Viton/Teflon	Du Pont
Neoprene (chloroprene rubber)	Neoprene[a]	Du Pont Denka
Nitrile rubber (NBR)	Chemigum Hycar Krynac NYsyn Paracril	Goodyear B. F. Goodrich Polysar Copolymer Uniroyal
Polybutylene (PB)	...	Shell Chemical
Polyester elastomer	Hytrel	Du Pont
Polyethylene - HDPE - LDPE - LLDPE	... ...	Many Many Many
Polyvinyl chloride (PVC)	PVC[a]	Borden General Tire B.F. Goodrich Pantasote Tenneco Union Carbide
Thermoplastic elastomer	Santoprene TPR	Monsanto Uniroyal
Urethane	...	Many

[a] Generic name

often mixed on a mill or in an internal mixer, such as a banbury. The mixed compound is then converted continuously into sheeting 54 inches to 33 feet in width by hundreds of feet in length by calendering, extrusion, and spread coating. Descriptions of the manufacturing processes are presented in Section 3.4.4. A representative list of sheeting manufacturers is presented in Appendix II.

3.4.2.3 Fabrication

After manufacture and rolling, the narrow sheeting, up to 60 inches in width, is ready for fabrication into panels. In this step the sheeting is joined (seamed) together to form panels (up to 100 feet x 200 feet). The size of the panels is limited by weight (usually about 5,000 pounds) and the ability of a crew to place it in the field. Various seaming techniques can be employed including, but not limited to: heat seaming, fusion seaming, dielectric seaming, adhesive systems, bodied solvents and solvent welds. The method used should be fully specified, including the type of quality control to be used. Factory seams are usually more reliable than field seams, since they are made under carefully controlled conditions. If the area to be lined is small enough, the entire finished liner may be prefabricated in one piece, eliminating field seaming altogether; this is called a drop-in liner. The recent introduction of wide sheeting in 22-33 foot widths of some materials has made the fabrication of panels unnecessary. Such sheetings are brought to the site in large rolls and the seaming is performed in the field using thermal or fusion seaming methods.

3.4.2.4 Installation

After the raw materials are produced, compounded, converted into sheeting and fabricated into panels, the installation is the final step toward completing the liner project. The installation should be performed by an experienced liner installer or by a qualified specialty contractor whose experience is in liner installation, associated earthwork, and piping installation. However, installation is incomplete until all field seams have been inspected to the satisfaction of the end user or his representative. Air lancing, vacuum, mechanical, and ultrasonic methods have been used in the field to make 100% inspection of seams.

3.4.2.5. Engineering and design services

Another important segment of the liner industry is the engineering and design services that are furnished by various engineering and consulting firms. Such services can supply the designs of disposal sites and participate in the selection of the liner system to be used. They also can supply quality control services during the installation of the liners.

3.4.3 Polymers Used in Liner Manufacture

Polymers used in the manufacture of lining materials include a wide range of rubbers and plastics differing in polarity, chemical resistance, basic composition, etc. They can be classified into four types:

- Rubbers (elastomers) which are generally crosslinked (vulcanized).
- Plastics which are generally unvulcanized, such as PVC.
- Plastics which have a relatively high crystalline content, such as the polyolefins.
- Thermoplastic elastomers, which do not need to be vulcanized.

Table 3-6 lists the various types of polymers that are used, indicates whether they are used in vulcanized or nonvulcanized form, and whether they are reinforced with fabric. The polymeric materials most frequently used in liners are polyvinyl chloride (PVC), chlorosulfonated polyethylene (CSPE), chlorinated polyethylene (CPE), butyl rubber, ethylene propylene rubber (EPDM), neoprene, and high-density polyethylene (HDPE). The thickness of polymeric membrane for liners range from 20 to 120 mils, with most in the 20-60 mil range.

Table 3-6. POLYMERIC MATERIALS USED IN LINERS

Polymer	Use in liners		Fabric reinforcement	
	Thermoplastic	Vulcanized	With	W/O
Butyl rubber	No	Yes	Yes	Yes
Chorinated polyethylene	Yes	Yes	Yes	Yes
Chlorosulfonated polyethylene	Yes	Yes	Yes	Yes
Elasticized polyolefin (partially crystalline)	Yes	No	No	Yes
Elasticized polyvinyl chloride	Yes	...	Yes	No
Epichlorohydrin rubber	Yes	Yes	Yes	Yes
Ethylene propylene rubber	Yes	Yes	Yes	Yes
Neoprene (chloroprene rubber)	No	Yes	Yes	Yes
Nitrile rubber	Yes	...	Yes	...
Polyethylene (partially crystalline)	Yes	No	No	Yes
Polyvinyl chloride	Yes	No	Yes	Yes

Most polymeric lining materials are based on single polymers; however, blends of two or more polymers, e.g. plastic-rubber alloys, are being developed and used in liners. Consequently, it is difficult to make generic classifications based on individual polymers of the liners, although one polymer will generally predominate in the compound. Blending of polymers introduces the long-range possibility of the need for performance specifications. However, long-term liner performance in the field cannot, at the present time, be completely defined by current laboratory tests.

Most of the membrane liners currently manufactured are based on unvulcanized or uncrosslinked polymeric compounds and thus are thermoplastic. Even if the polymer in the vulcanized form is more chemically resistant, such as CPE and CSPE, it is generally supplied unvulcanized because it is easier to obtain reliable seams and to make repairs in the field. Thermoplastic polymers can be heat-sealed or seamed with solvent or bodied solvent (a solvent containing dissolved polymer to increase the viscosity and reduce the rate of evaporation). Crystalline sheetings, which are also thermoplastic, can only be seamed by thermal or fusion methods. Information on individual polymers and liners is presented in subsequent subsections. Subjects covered on each polymer are: composition, general properties and characteristics, general use, and specific use in liners.

3.4.3.1 Butyl rubber

Liners of butyl rubber were among the first synthetic liners; they were used for potable water impoundment and have been in this type of service for about 30 years (Smith, 1980). Butyl rubber is a copolymer of isobutylene (97%) with small amounts of isoprene introduced to furnish sites for crosslinking (Morton, 1973, pp. 249-59). The important properties of butyl rubber relative to its use as a liner are:

a. Low gas and water vapor permeability.
b. Thermal stability.
c. Ozone and weathering resistance.
d. Chemical and moisture resistance.
e. Resistance to animal and vegetable oils and fats.

It is generally compounded with fillers and some oil, and vulcanized with sulfur. Butyl rubber vulcanizates are highly swollen by hydrocarbon solvents and petroleum oils, but are only slightly affected by oxygenated solvents and other polar liquids. Butyl rubber vulcanizates also have high resistance to mineral acids, high tolerance to extreme temperatures, retention of flexibility throughout service life, good tensile strength, and desirable elongation qualities.

Butyl rubber liners are vulcanized and manufactured in both fabric-reinforced and unreinforced versions. As they require special room temperature vulcanizing adhesives, they are difficult to seam and to repair.

3.4.3.2 Chlorinated polyethylene

Chlorinated polyethylene (CPE) is produced by a chemical reaction between chlorine and a high-density polyethylene. Presently available polymers contain 25-45% chlorine and 0-25% crystallinity. CPE is compounded and used in both thermoplastic and crosslinked compositions. CPE can be crosslinked with peroxides but, in liner compositions, it is generally used as a thermoplastic.

Since CPE is a completely saturated polymer (no double bonds) it weathers well and is not susceptible to ozone attack. Compounds of this polymer can have good tensile strength and elongation. Chlorinated polyethylene is resistant to deterioration by many corrosive and toxic chemicals. Because CPE liner compounds contain little or no plasticizer, they have good resistance to growth of mold, mildew, fungus, and bacteria. Membranes of CPE can also be formulated to withstand intermittent contact with aliphatic hydrocarbons and oils. Continuous exposure to aromatics will shorten the service life of the liner and, in most cases, CPE liners are not recommended for containment of aromatic hydrocarbon liquids (Dow, 1977).

CPE can be compounded with other polymers, making it a feasible base material for a broad spectrum of liners. CPE can be alloyed with PVC, PE and numerous synthetic rubbers. Nevertheless, at least half the polymer content of CPE liners is CPE resin. CPE membranes are available in varied thicknesses in unreinforced or fabric-reinforced versions. As membranes of CPE are generally unvulcanized, they can be seamed by bodied-solvent adhesives, solvent welding, or by heat sealing with an air heat gun or by dielectric means. CPE is widely used in minor amounts to improve the environmental stress crack resistance and softness of ethylene polymers and to improve the cold crack resistance of flexible polyvinyl chloride.

3.4.3.3 Chlorosulfonated polyethylene (CSPE)

Chlorosulfonated polyethylenes are a family of polymers prepared by reacting polyethylene in solution with chlorine and sulfur dioxide. Presently available CSPE polymers contain from 25 to 43% chlorine and from 1.0 to 1.4% sulfur. They are used in both thermoplastic (uncrosslinked) and crosslinked (with metal oxides) compositions. Thermoplastic CSPE is more sensitive to temperatures than other commonly-used elastomers. It is generally tougher at room temperature, but softens more rapidly as temperatures are increased (Morton, 1973, pp 337-8).

Chlorosulfonated polyethylene (CSPE) is characterized by ozone resistance, light stability, heat resistance, good weatherability, and resistance to deterioration by corrosive chemicals, e.g. acid and alkalies. It has good resistance to growth of mold, mildew, fungus, and bacteria. Membranes of this material are available in both vulcanized and thermoplastic forms, but primarily in the latter. Usually, they are reinforced with a polyester or nylon scrim and generally contain at least 45% of CSPE polymer. The fabric reinforcement gives needed tear strength to the sheeting for use on slopes, and reduces the distortion resulting from shrinkage when placed on the base and when exposed to the heat of the sun. The thermoplastic version is available in "potable" and "industrial" grades. The latter is more suitable for lining industrial and hazardous waste impoundments.

CSPE can be seamed by heat sealing, dielectric heat sealing, solvent welding, or by using "bodied" solvent adhesive. Membranes of this polymer do not crack or fail at extreme temperatures or from weathering. Disadvantages of unreinforced CSPE membranes are low tensile strength and a tendency to shrink on exposure to sunlight due to the heat absorbed. Also, thermoplastic CSPE tends to harden on aging, due to crosslinking by moisture, ultraviolet radiation, and heat and has relatively poor resistance to oils. The hardening can cause problems in repairing damaged sheetings due to crosslinking of CSPE, which can make it insoluble and difficult to heat seal.

Membranes of CSPE are available in colors other than black, without appreciable loss of other desirable characteristics (Du Pont, 1979).

3.4.3.4 Elasticized polyolefins

Elasticized polyolefin is a blend of rubbery and crystalline polyolefins. This polymeric material was introduced in 1975 as a black unvulcanized, thermoplastic liner, which readily and easily heat sealed with a specially designed heat welder in the field or at the factory. It has a low density (0.92) and is highly resistant to weathering, alkalis, and acids (Haxo et al, 1977). This membrane is unsupported and was manufactured by blow extrusion and supplied in sheets 20 mil thick, 20 feet wide, and up to 200 feet long (Du Pont, 1979), which are shipped to the site for assembly on the field.

Some difficulties were encountered with elasticized polyolefin in low temperatures and high winds, in oily environments, and in adhesion to structures. This type of liner was removed from the market, but it is expected that a modified version will be again manufactured.

3.4.3.5 Epichlorohydrin rubbers (CO and ECO)

Included in this classification are two epichlorohydrin-based elastomers which are saturated, high molecular weight, aliphatic polyethers with chloromethyl side chains. The two types include a homopolymer and a copolymer of epichlorohydrin and ethylene oxide. These materials are vulcanized with a variety of reagents that react difunctionally with the chloromethyl group, including diamines, urea, thioureas, 2-mercaptoimidazoline, and ammonium salts.

Epichlorohydrin elastomer vulcanizates exhibit the following characteristics:

a. Resistance to hydrocarbon solvents, fuels and oils.
b. Ozone and weathering resistance.
c. Low rate of gas/vapor permeability.
d. Thermal stability.
e. Good tensile and tear strength.

Epichlorohydrin rubber has a high tolerance for temperature extremes and retains its flexibility at extreme temperatures throughout its service life. The homopolymer has a performance range of 0 to 160°C. The copolymer shows improved low temperature flexibility and is recommended for service from -40 to 105°C. Membranes of epichlorohydrin elastomer are seamed with room temperature vulcanizing adhesives.

3.4.3.6 Ethylene propylene rubber (EPDM)

Ethylene propylene rubbers are a family of terpolymers of ethylene, propylene, and a minor amount of nonconjugated diene hydrocarbon. The diene supplies double bonds to the saturated polymer chain to supply chemically active sites for vulcanization, usually with sulfur. These rubbers vary in ethylene:propylene ratio, in the type and amount of the third monomer, and in molecular weight. Although EPDM liners are generally based on vulcanized compounds, thermoplastic EPDM liners are also available. Both versions are manufactured as fabric-reinforced and unsupported sheeting.

Liners based on vulcanized EPDM compounds have excellent resistance to weather and ultraviolet exposure and, when compounded properly, resist abrasion and tear. EPDM liners tolerate extremes of temperature, and maintain their flexibility at low temperatures. They are resistant to dilute concentrations (10% by weight) of acids, alkalis, silicates, phosphates, and brine, but are not recommended for petroleum solvents (hydrocarbons) or for aromatic or halogenated solvents.

Vulcanized EPDM membranes require the use of special cements and careful application to assure satisfactory field seaming. The proposed seam construction should be tested in the service environment to assure durability. Thermoplastic EPDM liners are seamed by thermal methods.

Because of its excellent ozone resistance, minor amounts of EPDM are sometimes added to butyl to improve the weather resistance of the latter.

3.4.3.7 Neoprene

Neoprene is the generic name of synthetic rubbers based upon chloroprene. These rubbers are vulcanizable, usually with metal oxides, but also with sulfur. They closely parallel natural rubber in mechanical properties, e.g. flexibility and strength. However, neoprene is superior to natural rubber in its resistance to oils, weathering, ozone, and ultraviolet radiation. Neoprene is resistant to puncture, abrasion, and mechanical damage. Neoprene membranes have been used primarily for the containment of wastewater and other liquids containing traces of hydrocarbons. They also give satisfactory service with certain combinations of oils and acids for which other materials do not provide long-term performance (Lee, 1974).

Neoprene sheeting for liners is vulcanized, thus vulcanizing cements and adhesives must be used for seaming.

3.4.3.8 Nitrile rubber

This class of polymers is a family of copolymers of butadiene and different amounts of acrylonitrile ranging from 18 to 50%. The principal feature of these copolymers is their oil resistance, which increases with increasing acrylonitrile content. Nitrile rubber is prepared by emulsion polymerization at different temperatures.

In most applications, nitrile rubber is compounded with plasticizers and is vulcanized. However, it is also blended with other polymers such as polystyrene, phenolics, and PVC to produce thermoplastic compositions that range in flexibility from rubbery compositions to hard impact-resistant plastics.

Nitrile rubber is used by the lining industry generally in blends of polymers to produce thermoplastic sheetings which feature oil resistance. The nitrile rubber is mixed with PVC in amounts less than 50% to yield compounds in which it acts as a nonmigrating and nonextractable plasticizer.

3.4.3.9 Polyethylene

Polyethylene is a thermoplastic crystalline polymer based upon ethylene. It is made in three major types: (1) low-density polyethylene (LDPE), (2) linear low-density polyethylene (LLDPE), and (3) high-density polyethylene (HDPE). The properties of a polyethylene are largely dependent upon crystallinity and density. Of the three types, high-density polyethylene polymers exhibit the greatest resistance to oils, solvents, and permeation by water vapor and gases. Unprotected clear polyethylene degrades readily on outdoor exposure, but the addition of 2 to 3% carbon black can produce improved ultraviolet light protection. Polyethylenes, as generally used, are free of additives such as plasticizers and fillers.

LDPE and HDPE types of polyethylene have been used as liners. Nonfabric-reinforced membranes of low-density polyethylene have been used for 25 to 30 years (Hickey, 1969) in lining canals and ponds. The low-density polyethylene (LDPE) available in thin sheeting tends to be difficult to handle and to field seam. Also, it is easily punctured under impact such as when rocks are dropped on the lining; however, it has good puncture resistance when buried. Linings of high-density polyethylene (HDPE), which have recently been introduced, are available in sheetings of 20 to 120 mils in thickness; special seaming equipment has been developed for making seams of these sheetings both in the factory and in the field. This type of liner is stiff compared to most of the other membranes described. Liner materials of LLDPE, a recently developed version of polyethylene, have not as yet been introduced on the market in thicknesses of 20 mils or greater.

3.4.3.10 Polyvinyl chloride

The polymer polyvinyl chloride is produced by any of several polymerization processes from vinyl chloride monomer (VCM). It is a versatile thermoplastic, which is compounded with plasticizers and other modifiers to produce a wide range of physical properties.

PVC liners are produced in roll form in various widths and thicknesses. Most liners are used as unsupported sheeting, but fabric reinforcement has been used. PVC compounds contain 25% to 35% of one or more plasticizers to make the sheeting flexible and rubber-like. They also contain 1% to 5% of a chemical stabilizer and various amounts of other additives. The PVC compound should not contain any water soluble ingredients. A wide choice of plasticizers can be used in PVC sheeting, depending upon the application and service conditions under which the PVC compound is to be used. Plasticizer loss during service is a source of PVC liner deterioration. There are three basic mechanisms for plasticizer loss: volatilization, extraction, and microbiological attack. The use of the proper plasticizers and an effective biocide can virtually eliminate microbiological attack and minimize volatility and extraction. The PVC polymer, itself, is not affected by these conditions. It is affected, however, by ultraviolet exposure.

The principal reason for loss of plasticizer is by volatilization in the heat of the sun rather than solution in the waste fluid. Carbon black prevents ultraviolet attack but does cause the absorption of solar energy raising the temperature to a high level to cause vaporization of plasticizer. A soil or other suitable cover material used to bury the liner protects it from ultraviolet exposure and reduces the rate of plasticizer loss. PVC sheeting is not recommended for exposure to weathering and ultraviolet light conditions during its service life. In some burial tests and in some liner applications, PVC sheetings have become stiff, presumably due to loss of plasticizers; some plasticizers can be degraded by microrganisms, while others can be extracted, to a limited extent, by water.

Plasticized PVC sheeting has good tensile, elongation, and puncture and abrasion resistance properties. It is readily seamed by solvent welding, adhesives, and heat and dielectric methods.

PVC membranes are the most widely used of all polymeric membranes for waste impoundments. They show good chemical resistance to many inorganic chemicals (Chan et al, 1978, p 19); however, they are attacked by many organic chemicals, particularly hydrocarbons, solvents, and oils which extract the plasticizer. Special compounds of PVC are available, designated as Oil-Resistant PVC (PVC-OR), that possess high resistance to oil attack. These "oil-resistant" grades of sheeting must be made with "specialty" plasticizers; the PVC polymer is inherently resistant to the effects of oils.

Polymers such as nitrile rubber, CPE and ethylene vinyl acetate (EVA) interpolymer may be used to replace the liquid plasticizers so that the PVC liner is not affected by the waste fluid.

3.4.3.11 Thermoplastic elastomers (TPE)

Thermoplastic elastomers are a relatively new class of rubbery materials (Walker, 1979). They include a wide variety of polymeric compositions from highly polar materials, such as the polyester elastomers, to the nonpolar materials, such as ethylene-propylene block polymers. These polymers are thermoplastic and nonvulcanized. They are processed and shaped at relatively high temperatures at which they are plastic; when they are cooled to normal ambient temperatures, they behave like vulcanized rubbers. Products made of these polymers have an upper temperature limit which occurs substantially above the temperatures encountered in waste disposal facilities.

Of particular potential interest for use in liners are the polyolefin thermoplastic elastomers, such as thermoplastic EPDM, which are probably related to the elasticized polyolefins, and nitrile rubber/PVC blends for oil resistant liners. Such liner materials are now under development and testing.

Nitrile/PVC thermoplastic elastomer blends have excellent oil, fuel, and water resistance with high tensile strength and excellent resistance to ozone and weathering. Blends tend to stiffen at low temperatures but remain serviceable.

As with liners of other thermoplastic polymers, liners of thermoplastic elastomers can be heat sealed to make seams and should be easy to repair; however, their durability in various chemical environments remains to be tested.

3.4.4 Membrane Manufacture

The three basic methods used in the manufacture of polymeric sheeting for liner use are calendering, extrusion, and spread or knife coating. Calendering is used in forming both unsupported and fabric-reinforced sheeting, whereas extrusion is only used in making unsupported sheeting. Spread coating is used for making fabric-reinforced sheeting in which the fabric is comparatively tight, i.e. the number of thread ends per inch is greater than 20.

Calendering is the most common method of forming the sheeting. In this process, heated rubber or elastic compounds are passed between the heated rolls of a calender to form a sheet of predetermined thickness. A calender usually consists of three to four rolls, as shown in Figure 3-4. The arrangement for preparing a single-ply sheeting on a 3-roll calender is shown in Figure 3-5. Unsupported sheeting is usually of single-ply construction; however, some manufacturers have resorted to multiple plying of unsupported liners to eliminate the formation of pinholes through the sheet. By manufacturing sheeting in this manner, the probability of a pinhole in one ply coinciding with a pinhole in another is remote.

Reinforcing fabric can be placed between the plies of the polymeric compound to produce a supported liner. In this case, sufficient material must be placed on both sides of the fabric so that pinholes are not generated between the fabric and the outside of the sheeting. Also, there should be sufficient compound present to strike through the open weave of the fabric and achieve direct contact of the rubber on both sides of the fabric. Fabric reinforcement is usually achieved through the use of open fabrics or scrim of nylon, polyester, polypropylene, or glass fiber. The thread count or ends per inch usually range from 6 x 6 to 10 x 10 per inch, but some are 20 x 20 ends per inch. Figure 3-6 shows several types of fabric. A coating is applied to the finished fabric after weaving in order to tack the yarns in place so that the finished fabric construction pattern will not lose its shape. Different coating formulations are used, depending on the end use. Fabrics to be used with vulcanized elastomeric lining materials are usually treated with an adhesive coating which chemically reacts with the membrane material during the curing cycle to produce adhesion to the polymer compound.

The extrusion technique is used primarily with polyolefins, such as polyethylene, and with elasticized polyolefin. For thinner films, a tube of film is produced and slit to form a sheet. For the thicker gage polyethylenes, thick sheets are extruded directly with proprietary extruding equipment. Some manufacturers set up special straining operations to clean out grit that may be in the compound. This operation immediately precedes the calendering or extrusion. In this step, grit and other coarse particles are screened out to yield a clean compound for the calender or extruder.

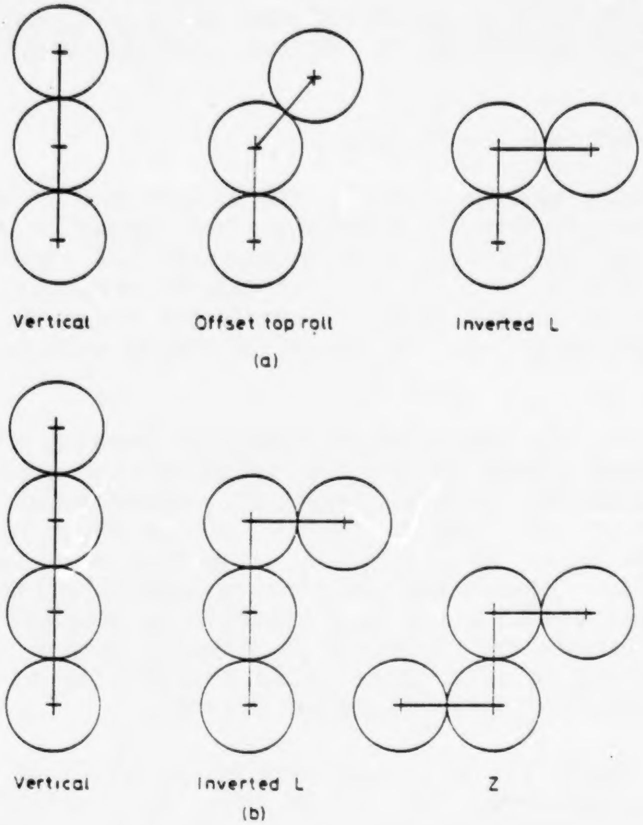

Figure 3-4. Roll configuration of calenders: (a) three-roll calenders, and (b) four-roll calenders (Blow, 1971).

Spread coating is performed only on fabrics having high numbers of thread ends per inch. In this process, the coating compound is applied as a viscous "dough" made of a high concentration of the compound dispersed in a solvent. The fabric is first passed over a spreader bar to remove wrinkles and creases and then passed beneath a stationary blade which spreads the compound and controls the thickness of the polymer coating. The solvent is evaporated by drawing the coated fabric through a heated chamber and the solvent is recovered. Upon removal from the heated areas, the sheeting is cooled and rolled (Blow, 1971, p 285).

3.4.5 Testing of Flexible Polymeric Membranes

3.4.5.1 Introduction

Because of the wide range of compositions and constructions of flexible polymeric membrane liners that are currently available and those being developed for lining waste impoundments, testing of the membranes is needed for a number of purposes. The liner manufacturer needs to test the sheeting as he uses new polymers and develops new compounds and constructions. He needs

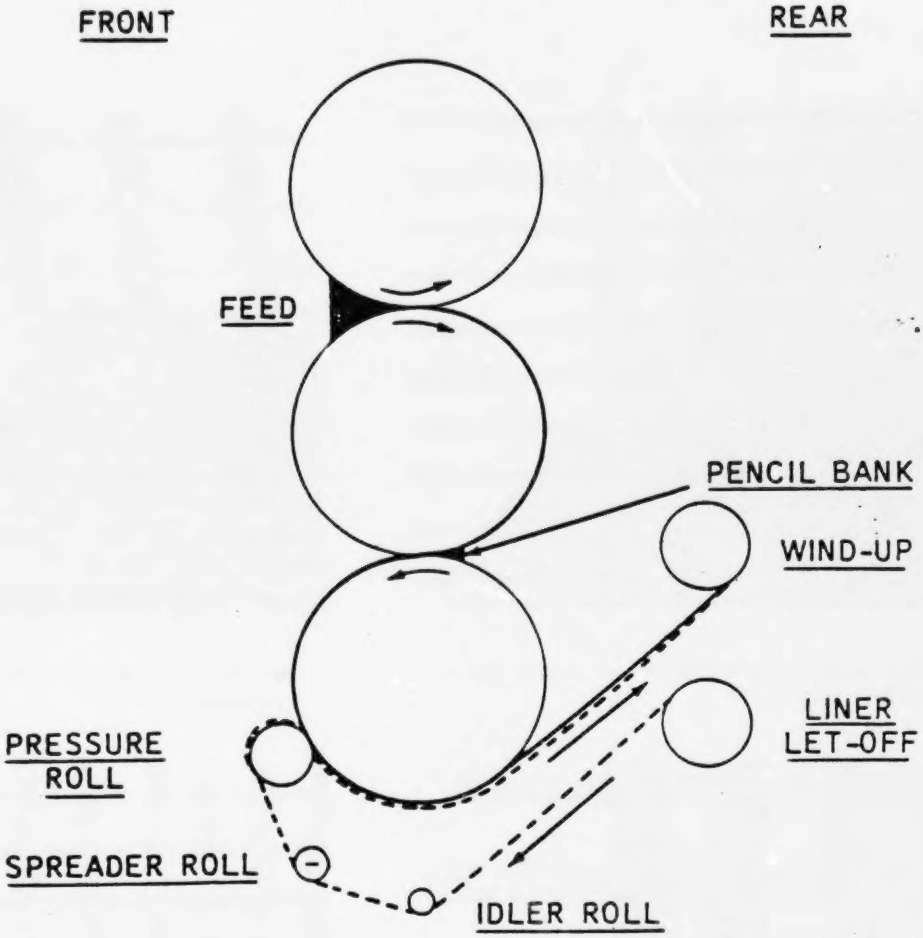

Figure 3-5. Calender arrangement for coating sheeting on one-pass or ply-up with pencil bank (Banks, 1966).

tests to control the quality of the liner he is manufacturing. Before sheeting is selected and purchased, the site-owner needs methods to test sheetings to determine whether or not one or more meets the requirements of the design. These test methods may take the form of compatibility studies between the waste and the lining materials to try to predict the performance of a potential sheeting in service. The sheeting may be tested to characterize or fingerprint the compound. A sample taken from a sheeting in the process of being installed may be tested by the owner to assure the quality of the material being placed in the field. Samples may be tested during service to assess the performance or condition of the liner. The testing of materials, particularly with reference to polymeric membranes for the lining of waste disposal facilities, is described by Haxo (1981).

The testing of a polymeric membrane liner at the time of placement can be used 1) as a means of characterizing the specific sheeting and 2) as a baseline for monitoring the effects of exposure on the liner. Eventually it is expected

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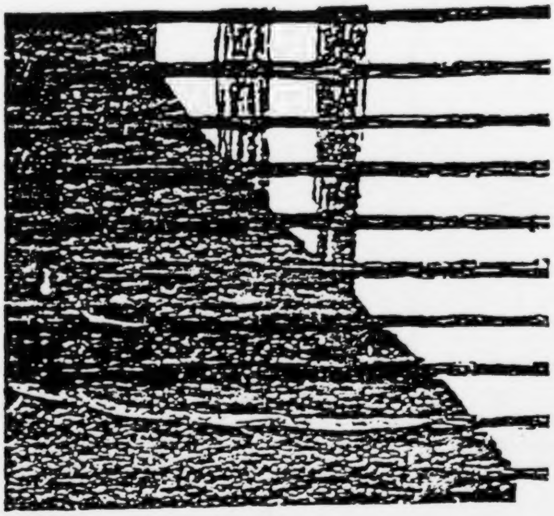
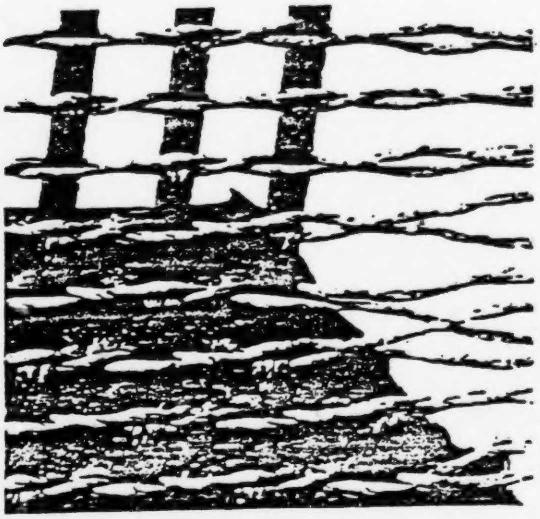
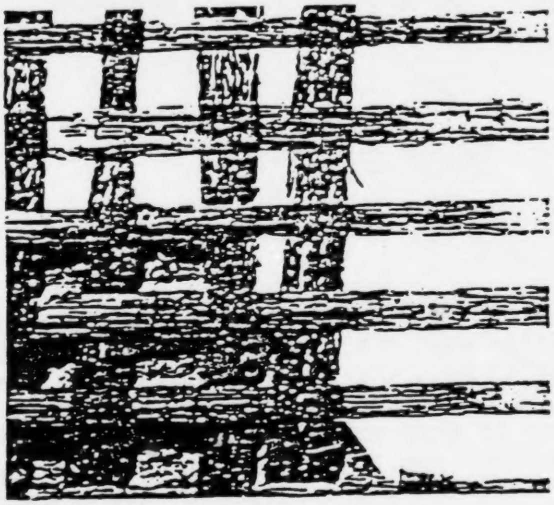


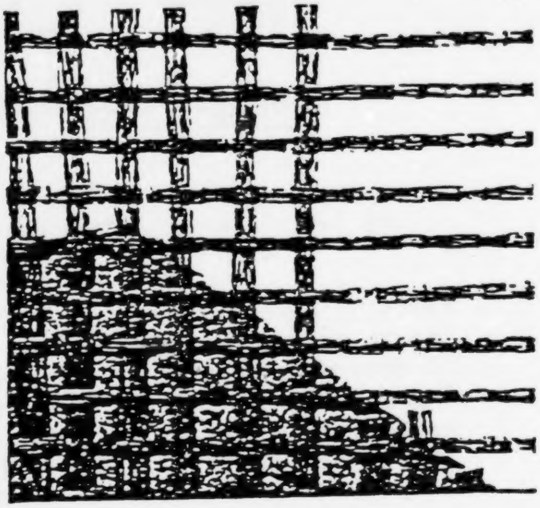
Manufacturer F. 30 mils (0.76 mm), B-5602. Photo P222-D-65685



Manufacturer A. 60 mils (1.52 mm), B-4606. Photo PX-D-68886



Manufacturer G. 30 mils (0.76 mm), B-5540. Photo PX-D-68887



Manufacturer H. 30 mils (0.76 mm), B-5560. Photo PX-D-68888

Figure 3-6. Nylon-reinforced, butyl lining samples showing different weaves and weights of nylon used by four manufacturers at 6x magnification. (Hickey, 1971).

that correlations will be developed between the simulation tests and field performance to yield a body of tests which can effectively predict the field performance of a lining material in a given situation.

Polymeric membranes are tested in accordance with many different methods, depending upon the type of membrane liner; sheetings used as liners have been developed by three different industries, i.e. rubber, plastics, and textile. Each has developed standard test methods. Some test methods for one type of sheeting are not appropriate for other types; for instance, using a dumbbell with a quarter-inch restricted area, such as is used in the testing of rubber vulcanizates, is not satisfactory for measuring the tensile properties of fabric-reinforced materials.

From the point of view of testing, there are four basically different types of polymeric membranes:

- Crystalline polymers without fabric reinforcement.
- Fabric-reinforced sheetings which can be based upon either crosslinked or thermoplastic polymers.
- Thermoplastics or uncrosslinked polymers without fabric reinforcement.
- Vulcanized or crosslinked elastomers without fabric reinforcement.

The methods used for testing polymeric lining materials can be grouped into four categories:

- Analyses to assess composition and to fingerprint.
- Tests of physical properties, including information regarding construction and dimensions of the membrane.
- Tests to determine properties in stress environments and aging tests in specific exposures or compatibility tests.
- Tests of durability of lining materials under conditions that simulate actual field service.

These tests can include measurements of the following properties:

- Analytical properties before and after exposure to different environments.
    - Ash.
    - Differential scanning calorimetry if liner material is crystalline.
    - Extractables.
    - Gas chromatography and gas chromatograph/mass spectroscopy.
    - Specific gravity.
    - Thermogravimetric analysis.
    - Volatiles.
- Physical properties before and after exposure to different environments:
    - Burst strength (hydrostatic resistance).
    - Dimensional stability.

- Hardness.
- Modulus of elasticity if liner material is crystalline.
- Ply adhesion for fabric-reinforced sheeting.
- Puncture resistance.
- Seam strength of factory and field-prepared seams.
- Tear resistance.
- Tensile properties.
- Thickness.
- Water vapor transmission.

The measurement of these properties represents a body of tests which can be used to monitor the effects on a liner of an environmental exposure. In addition, a variety of tests are performed after exposure to different environmental conditons:

- Environmental and aging effects upon properties:
    - Environmental stress cracking if liner material is crystalline.
    - High temperature.
    - Low temperature.
    - Water absorption.
- Tests of durability under different conditions that simulate service:
    - Retention of selected properties on or during the burial test.
    - Retention of selected properties on or during the immersion in water, standard test liquids, and waste liquids.
    - Retention of selected properties on or during the outdoor roof exposure.
    - Retention of selected properties on or during the pouch test, except vulcanized sheetings.

A change in one property during an exposure is usually accompanied by changes in other properties, but at this stage no one property has been correlated with liner performance in the field. In the subsequent subsections, we discuss these properties and how they are tested. A list of specific test methods can be found in Table 3-7. Many of the physical and simulated service tests that are used in the rubber industry are described in DuPont (1963).

3.4.5.2 Analytical properties of polymeric membrane liners

Volatiles. "Volatiles" is the percent weight lost by a specimen of liner on drying in a desiccator at 50°C and then heating in an oven at 105°C. If the liner has been exposed and absorbed volatile liquids the portion of weight lost in the desiccator represents the water fraction and the portion lost at 105°C represents the low-boiling organic fraction that the liner absorbed. Changes in the volatile fraction can be used as a means of monitoring a material during exposure to waste liquids. The percent of swell can be estimated from the volatiles by dividing that number by the nonvolatile fraction; the amount of plasticizer lost to the waste liquid can be calculated

TABLE 3-7. APPROPRIATE OR APPLICABLE TEST METHODS FOR UNEXPOSED MEMBRANE LINERS

Liner material property	Membrane liner without fabric reinforcement Thermoplastic	 Crosslinked	 Crystalline	Fabric-reinforced
Analytical properties				
Volatiles	MTM-1[a]	MTM-1[a]	MTM-1[a]	MTM-1[a] (on selvage and reinforced sheeting)
Extractables	MTM-2[b]	MTM-2[b]	MTM-2[b]	MTM-2[b] (on selvage and reinforced sheeting)
Ash	ASTM D297, ¶ 34	ASTM D297, ¶ 34	ASTM D297, ¶ 34	ASTM D297, ¶ 34 (on selvage)
Specific gravity	ASTM D792, Mtd A	ASTM D297, ¶ 15	ASTM D792, Mtd. A	ASTM D792, Mtd A (on selvage)
Physical properties				
Thickness - total	ASTM D638	ASTM D412	ASTM D638	ASTM D751, ¶ 6
Coating over fabric	na	na	na	Optical Method
Tensile properties	ASTM D882, ASTM D638	ASTM D412	ASTM D638 (mod)	ASTM D751, Mtd A and B (ASTM D638 on selvage)
Tear resistance	ASTM D1004 (mod)	ASTM D624, Die C	ASTM D1004	ASTM D751, Tongue Mtd.
Modulus of elasticity	na	na	ASTM D882, Mtd A	na
Hardness	ASTM D2240 Duro A or D	ASTM D2240 Duro A or D	ASTM D2240 Duro A or D	ASTM D2240 Duro A or D (selvage only)
Puncture resistance	FTMS 101B, Mtd 2065	FTMS 101B, Mtd 2065	FTMS 101B, Mtd 2065	FTMS 101B, MTD 2065
Hydrostatic resistance	ASTM D751, Mtd A	ASTM D751, Mtd A	ASTM D751, Mtd A	ASTM D751, Mtd A
Seam strength				
Shear	ASTM D816, Mtd B (mod) ASTM D882, Mtd A (mod)	ASTM D816, Mtd B (mod) ASTM D882, Mtd A (mod)	ASTM D816, Mtd B (mod) ASTM D882, Mtd A (mod)	ASTM D816, Mtd B (mod) ASTM D882, Mtd A (mod)
Peel	ASTM D413, Mach Mtd Type 1 (mod) ASTM D1876 (mod)	ASTM D413, Mach Mtd Type 1 (mod) ASTM D1876 (mod)	ASTM D413, Mach Mtd Type 1 (mod) ASTM D1876 (mod)	ASTM D413, Mach Mtd Type 1 (mod) ASTM D1876 (mod)
Ply adhesion	na	na	na	ASTM D413, Mach Mtd Type 1 ASTM D751, ¶ 39-42
Environmental and aging effects				
Ozone cracking	ASTM D1149	ASTM D1149	na	ASTM D1149
Environmental stress cracking	na	na	ASTM D1693	na
Low temperature testing	ASTM D1790	ASTM D746	ASTM D1790 ASTM D746	ASTM D2136
Tensile properties at elevated temperature	ASTM D638 (mod)	ASTM D412 (mod)	ASTM D638 (mod)	ASTM D751 Mtd B (mod)
Dimensional stability	ASTM D1204	ASTM D1204	ASTM D1204	ASTM D1204
Air oven aging	ASTM D573 (mod)	ASTM D573 (mod)	ASTM D573 (mod)	ASTM D573 (mod)
Water vapor transmission	ASTM E96, Mtd BW	ASTM E96, Mtd BW	ASTM E96, Mtd BW	ASTM E96, Mtd BW
Water absorption	ASTM D570	ASTM D471	ASTM D570	ASTM D570
Immersion in standard fluids	MTM-3[c]	MTM-3[c]	MTM-3[c]	MTM-3[c]
Soil burial	ASTM D3083	ASTM D3083	ASTM D3083	ASTM D3083

na = Not applicable.

[a] Matrecon Test Method-1, see Appendix III-D.

[b] Matrecon Test Method-2, see Appendix III-E.

[c] Matrecon Test Method-3, see Appendix III-A.

from an analysis of the "extractables" *(see below) if the original plasticizer* content is known.

Ash. The ash content of a liner material is the fraction that remains after a sample is thoroughly burned at an elevated temperature, e.g. 550°C. The ash content is usually made up of inorganic materials that have been used as fillers or as curatives in the polymeric coating compound. As different manufacturers formulate their compounds differently, determining the ash content can be a way to "fingerprint" a polymeric liner compound. The residue obtained by ashing can be retained for further analyses, such as metals content, needed for further identification and to determine the trace elements that may have been absorbed by the liner. The test method described in ASTM D297, Paragraph 34, is generally followed in performing this analysis.

Extractables. The extractable content of a polymeric sheeting is the fraction that can be extracted from a sample of the liner with a solvent that neither decomposes nor dissolves the liner. A recommended test procedure for this analysis of unexposed sheeting, showing the specific solvents that can be used for each type of polymer, is given in Appendix III-E. "Extractables" consist of plasticizers, oils, or other solvent-soluble constituents that impart or help maintain specific properties, such as brittleness or processability. A measurement of extractable content and analytical study of the extract can be used as part of the "fingerprint" of a sheeting. An important use of this test is to monitor the effects of exposure to waste liquids. During exposure to a waste liquid, constituents in the original liner compound may be extracted resulting in a change in properties of the liner. For instance, during exposure to some waste liquids, the plasticizer can be extracted from a PVC liner and cause the sheeting to harden, become brittle, and shrink, thus increase the possibility of failure. The loss of plasticizer will appear in the analysis as a lower extractable content. Another possible effect of an exposure that can be monitored by measuring the extractable content is the case where a sheeting absorbs non-volatile elements such as higher molecular weight oils from a waste and becomes soft. Softening of the liner is also incurred by the absorption of waste which may include both water and organic compounds. To determine the extractables of an exposed liner, the volatile fraction must be removed. A flow diagram of a recommended analysis of exposed polymeric liner materials is presented in Appendix III-F. This procedure features the initial removal of absorbed wastes by drying a specimen of the liner in a desiccator at 50°C followed by the removal of the organic volatiles by heating at 105°C. The extraction is then performed on the devolatilized sample. The organic volatiles and extracts can be analyzed separately if needed by infrared and gas chromatography.

Gas chromatograph/mass spectroscopy (GC/MS). The gas chromatograph is capable of separating a mixture of gases into chemically pure components by the retention time of the component on the chromatographic column installed in the instrument. The information is sufficient to prove that an unknown and a standard are different, should they exhibit different different retention times. It is not sufficient to prove conclusively that an unknown and standard having the same retention time are the same. The extra information required to show conclusively identity must be provided by a more powerful detector than coventional flame ionization or thermal conductivity detectors.

The mass spectrometer is ideally suited to this purpose. It operates by destructively ionizing the pure organic fractions arriving at it from the GC column, and then further separating the molecular fragments on the basis of their ionic charge and molecular weight. The data resulting is highly complex and very reproducible. It can be used 1) to identify the component on the basis of these data alone, as a "fingerprint" and, with access to a library or computer data base, also to identify conclusively the component. In either case, the reproducibility and high information content of the GC/MS data makes the probability of identification errors very low.

Thermogravimetric analysis (TGA). TGA is a technique for assessing the composition of materials by their loss in weight on heating at a controlled rate in an inert or an oxidizing atmosphere. For example, when a material is heated in an inert atmosphere from room temperature to 600°C at a controlled rate, it will volatilize at different temperatures until only carbon, char, and ash remain. The introduction of oxygen into the system will burn off the char and carbon black. Thus, from the weight-time curve which can be related to weight and temperature, the amounts of volatiles, plasticizer, polymer, carbon black, and ash can be calculated. In some cases, thermogravimetric analysis can replace measurements of the volatiles, ash, and extractables contents discussed above. The TGA curve and the derivative of the TGA curve can thus be used as part of a "fingerprint" of a polymeric composition. This technique is described by Reich and Levi (1971).

Differential scanning calorimetry (DSC). DSC is a thermal technique for measuring the melting point and the level of crystallinity in partially crystalline polymers, such as the polyolefins, e.g. polyethylene and polybutylene. This technique measures the heat of fusion of a crystalline structure. It can also give an indication regarding modification of crystalline sheeting with other polymers by alloying. Thus, this type of analysis can be used as a means of fingerprinting crystalline polymeric liner materials, particularly high-density polyethylene, and assessing the effects of aging and exposure to wastes. This equipment can also be used to measure second order transitions of polymers and plasticized polymers. This transition is the temperature at which a polymer converts from a brittle, glassy state to an amorphorus, rubbery state and is thus related to its low temperature properties. These techniques are described by Boyer (1977) and Ke (1971).

Specific gravity. Specific gravity and density are important, easy to determine, characteristics of a material which can give an indication of the composition and identification of a compound. On exposed liners, specific gravity can be measured only after the liner has been devolatilized. Care must be taken to thoroughly dry the specimen before placing it in the oven at 105°C to avoid bubbles forming in the sample. ASTM Method D792, Method A, and D297, Paragraph 15, are generally used in performing this test.

3.4.5.3 Physical properties of polymeric membrane liners

Tensile properties. Tensile properties of polymeric sheetings are measured in tension with a stress-strain tester. The properties that are measured depend on the type of polymeric sheeting and include the following:

- Tensile at fabric break (if fabric-reinforced).
- Elongation at fabric break (if fabric-reinforced).
- Tensile at yield (if a crystalline liner).
- Elongation at yield (if a crystalline liner).
- Tensile at break of sheeting.
- Elongation at break of sheeting.
- Modulus at specified elongations, e.g. 100% and 200%.

The test methods, including the test specimens, vary with the type of material The basic purpose for measuring tensile properties is that the test gives a good indication of the quality of a compound of a given polymer. Absolute tensile strength values from polymer to polymer should not be compared unless tensile strength is an important property in the performance of the product.

Tensile testing is probably the most widely used test method in the rubber and plastics industries for testing polymer compositions and products. It must be recognized that, even for a given polymeric material, the values for the tensile properties vary with speed of test, i.e. the rate of jaw separation, specimen size, direction of test with respect to the grain in the sheeting, temperature, and humidity.

Changes in tensile properties can be used to monitor the effects of exposure on a lining material. In many rubber and plastics applications, a 50% loss in tensile strength in elongation, or a 50% increase or decrease in modulus, indicates that the product has become unserviceable. These criteria are probably not applicable to liners; nevertheless, major changes in properties in relatively short times indicate the incompatibility of a liner and a waste.

The test procedures followed in determining tensile properties for the different types of sheetings are:

Thermoplastic sheeting:	ASTM D882 ASTM D638
Crosslinked rubber:	ASTM D412
Crystalline polymer:	ASTM D638
Fabric reinforced sheeting:	ASTM D751, Methods A and B
Selvage edge	ASTM D882, D638, or D412, depending on the type of polymer coating compound

Modulus of elasticity. The modulus of elasticity is a measure of the stiffness or rigidity of stiff materials such as HDPE; it is defined as the ratio of stress to corresponding strain in the part of the stress strain curve that behaves according to Hooke's law, i.e. the stress values are linear with respect to the spaces. It is also known as Young's modulus. ASTM D883, Method A, is followed in determining the modulus of elasticity of crystalline membranes.

Hardness. Hardness, in terms of the standard tests for hardness of polymeric materials, is the ability of a material to resist indentation by a small probe of specified shape and dimensions. Although no simple relationship exists between hardness as determined by indentation and other measured properties, it is related to Young's modulus (ASTM D1415-81). Hardness is an easily measured indicator of the quality of a polymeric material and can be used to monitor change in a material. ASTM D2240 is generally used to measure this property; the A scale is used for soft, rubbery materials and the D scale is used for hard materials, i.e. materials that are harder than 85 measured on the A scale.

Tear resistance. Tear resistance is a measurement of the force required to tear a specimen with or without a controlled flaw. The measurement serves as an indication of the quality of the compound and of the mechanical strength of a sheeting, particularly to the type of stresses encountered during installation. The measurement is also used to monitor the effects of an exposure on a material. The magnitude of the tear value is sensitive to the rate of test and the shape and size of the test specimen. Coated fabrics are normally run at 12 inches per minute. Unreinforced vulcanized sheetings are tested at 20 ipm. It is recommended that unreinforced thermoplastics be tested at 20 ipm and crystalline materials at 2 ipm. A variety of ASTM tests are used. Thermoplastics and crystalline materials are usually tested according to ASTM 1004; crosslinked rubber sheetings are tested according to ASTM D624, using Die C, and coated fabrics are tested according to ASTM D751, using a "tongue" specimen. Because of the low adhesion between the fabric and the polymer coating, the fabric pulls out of the polymer matrix resulting in the threads bundling at the tip of the tear and yielding excessively high test values. As a consequence, a larger specimen is used by the liner industry than is called for in the ASTM method.

Puncture resistance. Puncture resistance is a measurement of the force required to puncture a sheeting with a standard probe. The measurement serves to indicate the ability of a material to withstand puncture from above, e.g. equipment, foot traffic, deer hooves, etc and from below, e.g. by irregularities in the substrate, etc. Puncture resistance can be used to monitor the effects of an exposure on a sheeting. There is no universally accepted method for testing puncture resistance. We recommend and use the method described in Federal Test Method Standard 101B, Method 2065, for measuring puncture resistance, particularly of unreinforced sheetings. The usefulness of this test for fabric-reinforced flexible membrane is limited because of the openness of the weaves normally used. The hydrostatic resistance test described below is useful for coated fabric. Neither test, however, measures the resistance to puncture of a liner by a sharp object falling on the sheeting during installation. Our recommended method reflects more the resistance to a slow puncture.

Hydrostatic resistance tests. This test measures the hydrostatic pressure required to burst a specimen of sheeting. ASTM D751, Method A - Procedure 1, which is designed for fabric-reinforced sheeting, is commonly used to measure this property of most membrane liners.

Water vapor transmission. To measure water vapor transmission, ASTM E-96 Method BW is used. In this test, a cup with a membrane specimen cover is placed in an inverted position in a controlled temperature, humidity, and air stream. Loss in weight of water from the cup is observed as a function of time. This test is intended for those applications in which one side is wetted under conditions where the hydraulic head is relatively unimportant and the moisture transfer is goverened by water vapor diffusion forces. The driving force is supplied by the difference in the relative humidity on the two sides of the membrane.

3.4.5.4 Tests of membranes under environmental stress

Environmental stress-cracking. A stress-crack is defined as an external or internal crack in a plastic caused by tensile stresses less than its short-time mechanical strength. Under certain conditions of stress and exposure to soaps, oils, detergents, or other surface-active agents, certain grades of polyethylene in particular may fail by cracking. Proper selection of the polyethylene or addition of one of a variety of rubbery polymers can eliminate this deficiency. ASTM D1693 can be run to indicate the susceptibility of a polyethylene sheeting to environmental stress-cracking. In this test, specimens having a controlled imperfection are bent and exposed to the effects of a designated surface-active agent. Failure comes with a breaking of the specimen.

High-temperature properties. A liner material can encounter higher than normal temperature prior to installation, during installation, and during service. Thermoplastic liners, if allowed to be exposed to heat as rolled or folded panels prior to installation, such as being left in the sun, can block or stick together; when unfolded, a coated sheeting may split or an unsupported sheeting may tear and become unserviceable. During installation, the black sheeting can reach temperatures of more than 160°F (71°C). At such temperatures, tensile and tear strengths can be significantly lower than at normal test temperatures. Also, higher temperature can cause shrinkage and distortion of the sheeting. Appropriate tensile, modulus, and tear tests can be run at temperatures of 60°C or higher to determine the effects of elevated temperature.

Low temperature properties. Liners can encounter low temperatures before installation, during installation, and in some cases during service depending upon the climate in which they are installed.

Some lining materials are quite sensitive to low temperature, becoming stiff and even brittle on exposure to moderately low temperatures. The rate at which these changes take place, and the time it takes for a material to soften when its temperature is raised, vary. Some changes can take an extended time; consequently, short-term tests can be quite misleading.

A variety of tests exist for measuring the effects of low temperatures upon materials. Brittleness test methods are some of the most available. However, they vary greatly in low temperature soak time, rate of test, configuration of specimen, etc; consequently, even for a given polymer type, results can vary greatly, depending on thickness of specimen, time of soak and the specific test used. Some of the commonly used low temperature tests are:

ASTM D746 - Brittleness Temperature of Plastics and Elastomers by Impact.

ASTM D1034 - Stiffness properties of Plastics as a Function of Temperature by Means of a Torsion Test (also used on rubber compositions).

ASTM D1790 - Brittleness Temperature of Plalstic Film by Impact.

ASTM D2136 - Low Temperature Bend Test of Coated Fabrics.

ASTM D2137 - Brittleness Point of Flexible Polymers and Coated Fabrics.

Water absorption. Absorption of water can have adverse effects on many polymeric compositions. Since most waste fluids contain water, the effects of immersion in water on lining materials need to be determined. The effects of immersion are monitored in terms of either change in weight, change in dimensions, or both. A water absorption test is included to provide a relatively precise comparative index of all the sheetings in the test. Extended immersion periods are recommended. The test specimens are large enough to get a tensile dumbbell out of or to pull as a strip to get an indication of the effect of water absorption on tensile properties. Water absorption tests at elevated temperatures accelerate the effects of immersion in water. Prior testing has shown that water absorption tests run at 70°C are too severe as accelerated aging tests for most materials. We recommend performing water absorption tests on all the sheetings at room temperature (23°C) and at 50°C. Water absorption tests were run according to ASTM D471 and D570.

3.4.5.5 Testing of seam strength of factory and field systems

A critical factor in the functioning and durability of a polymeric membrane liner in service is the seam strength between assembled panels of the sheeting. Testing of seams is performed to ensure that the method of seaming a particular material is adequate. Testing of the seams also can be performed as part of immersion testing with wastes and with standard fluids, because the effect of the wastes on the seams can vary, particularly if the seams are fabricated with adhesives.

Seams are tested in shear and peel modes both dynamically, in which an increasing load is applied, and statically, where a constant load is applied and maintained. Elevated temperatures are often used in seam strength tests. The peel test of seam strength is significantly more sensitive to the effects of aging and exposure than shear testing.

Seam strength is run in shear according to ASTM D816, Method B (Modified) and D882, Method A (Modified). Seam strength in the peel mode is run according to ASTM D413, Method Type 1, and D1876.

3.4.5.6 Compatibility and Durability Tests

Tests for the compatibility of liner materials with wastes and their durability on long-term exposure are described in Chapter 4.

3.4.6 Seaming of Polymeric Liner Membranes

3.4.6.1 Introduction

Critical to the effective performance of polymeric membrane liners of impoundments and solid waste landfills is the construction of continuous watertight barriers of approximately uniform strength. As indicated in the discussion of membrane liners in subsection 3.4.2.2, in the case of most polymeric membrane liners, sheetings are manufactured in relatively narrow widths (less than 90 inches) that are seamed together in the factory to make large panels. These panels, in turn, are assembled at the disposal or impoundment site to make large, continuous sheets which can range up to many acres in area. Therefore, in a liner installed in this manner there are both factory and field seams. In the favorable factory environment, durable seams can be made by a variety of methods depending on the type of polymer. Seaming in the field can pose difficulties, largely due to variability in the ambient conditions. According to the available information, seams appeared to be the most likely source of liner problems and failure. Recently, several lining materials made in wider sheetings have been introduced, i.e., in widths ranging from 21 to 33 feet; these materials are brought to the site in large rolls and seamed in the field, thus eliminating factory seaming.

In order to function as a liner, a sheeting must have a bonding system which can be used to fulfill the following requirements:

1. The bond between the sheets or panels must be continuous for the length of the seam.
2. The bond between the sheets must approximate the strength of the sheeting and must maintain its strength throughout the service life of the sheeting.
3. The bond must be capable of being formed in the field.

A variety of bonding systems are used in the seaming of polymeric membranes. Selection of the optimum system for a given liner will depend largely on the polymer. Certain techniques or seaming systems are incompatible with certain liner materials. For instance, dielectric seaming cannot be used to seam a butyl rubber sheeting. In addition, some adhesives are designed for use with a specific sheeting and should not be used with other lining materials even though the two materials may be based on the same polymer. Manufacturers may recommend a specific seaming technique, a specific type of adhesive, or a variety of techniques or adhesives. For instance, the manufacturers of the

CPE sheeting used as a primary test specimen recommended three types of bonding systems and specific systems within each type.

The following is a list of seaming techniques that are currently used either in the factory to fabricate panels, or in the field to assemble the panels into a final liner, or both:

- Solvent "welding".
- Bodied solvents.
- Solvent cements.
- Contact cements.
- Vulcanizing adhesives.
- Tapes.
- Thermal techniques.
    Heat guns.
    Dielectric (factory).
    Fusion (field).

Mechanical methods for seaming, though adequate for water containment, are not considered adequate for seaming liners for waste storage and disposal facilities. Table 3-8 presents a list of the possible alternative methods for seaming polymeric materials depending upon the polymer, type of compound, and location of seaming, i.e. factory or field. Also indicated on the table are the systems included in the exposure tests.

3.4.6.2 Solvent "welding"

Solvent "welding" of thermoplastic sheetings can be achieved by coating the mating surfaces of the sheetings with a suitable solvent for the compound and then pressing the two surfaces together firmly by wiping or rolling.

The solvent, which solubilizes the surface of the sheeting and imparts some tack, can be applied either by a brush or with a squeeze bottle. Initial set-up time ranges from five minutes to an hour, depending on the type of material and environmental conditions. A few days are usually needed before the solvent evaporates completely from the joint and the seams achieve full strength. Because the technique requires a solvent which can dissolve the lining material itself, and because crosslinked polymers swell but do not dissolve, this technique can be used only with thermoplastic materials. Though this method can be used both in the field and in the factory, it is sensitive to the weather conditions in which it is used, e.g. temperature, humidity, and wind. Volatile solvents which may be desirable at lower temperatures will evaporate too quickly at higher temperatures or may fail to bond because of moisture condensation under humid conditions.

3.4.6.3 Bodied solvents

Similar to solvent "welding" is the use of bodied solvents to seam lining materials. A bodied solvent is essentially an adhesive based upon a solution of the liner compound to be seamed. The adhesive needs to be applied to both surfaces and the two surfaces pressed together after becoming tacky. There should not be evidence of surface "skinning" or drying of the adhesive when the two surfaces are joined. The basic advantage of a bodied solvent

TABLE 3-8. BONDING SYSTEMS AVAILABLE FOR SEAMING POLYMERIC MEMBRANE LINERS IN FACTORY AND FIELD

	Type of compound[a]	Place used	Solvents	Bodied solvents	Solvent cements	Contact cements	Vulcanizing adhesives	Tapes	Heat sealed	Dielectric	Fusion
Butyl rubber	XL	Factory	...	...	...	X	X	...	...	...	...
		Field	...	...	...	X	X	X	...	...	...
Chlorinated polyethylene	TP	Factory	X	X	X	X	...	...	X	X	...
		Field	X	X	X	X	...	X	X	...	...
Chlorosulfonated polyethylene	TP	Factory	X	X	X	X	...	...	X	X	...
		Field	X	X	X	X	...	X	X	...	...
Elasticized polyolefin	TP	Factory	...	...	...	X	...	...	X	...	...
		Field	...	...	...	X	...	...	X	...	...
Ethylene propylene rubber	XL	Factory	...	...	...	X	X	...	...	...	...
		Field	...	...	...	X	X	X	...	...	...
Low-density polyethylene	TP/CX	Factory	...	...	...	X	...	...	X	...	...
		Field	...	...	...	X	...	X	X	...	...
High-density polyethylene	TP/CX	Factory	...	...	...	...	...	...	...	...	X
		Field	...	...	...	...	...	...	...	...	X
Neoprene (polychloroprene)	XL	Factory	...	...	...	X	...	...	...	...	...
		Field	...	...	...	X	...	...	...	...	...
Poly(vinyl chloride)	TP	Factory	X	X	X	X	...	...	X	X	...
		Field	X	X	X	X	...	X	X	...	...

[a] XL = Crosslinked or vulcanized; TP = thermoplastic; CX = crystalline.

over a straight solvent is the increased viscosity of the solution which allows more control of the evaporation of the adhesive and aids in making seams on a slope. As with solvent "welding", this tecnhique can only be used with thermoplastic materials that can be dissolved in a suitable solvent. This technique can be used to seam sheeting in the factory and is particularly useful in the field.

3.4.6.4 Solvent cements and contact cements

"Solvent cements" is an expression used by the adhesive industry to refer to any of a large variety of adhesives that are applied dissolved in a nonaqueous solution. The strength of the bond is achieved either contemporaneously with or after the volatization of the solvent. Thus, a solvent cement can be anything from a solution of a thermoplastic resin to a contact cement. Two types of solvent cements are of interest to the lining industry:

- Contact cements.
- Cements that volatilize their solvent while forming the adhesive bond.

Surfaces to be bonded by the second type of adhesive are usually pressed together while the solvent cement is still "wet". Because polymeric membrane materials can have low permeability to a number of solvents, it is important to choose a solvent cement based on a solvent that can volatilize out of the seam assembly. This can happen when the solvent in the cement either dissolves or partially dissolves the surface of the sheeting and forms what might be called an "interpenetrating" bond with the lining material.

Contact cements are adhesives that are applied wet to surfaces of sheetings that are to bonded and allowed to dry to a "tacky" and solvent-free state before the two surfaces are joined. The use of this type of adhesive requires careful alignment of the lining material before bonding because the joined surfaces should not be realigned after assembly. After joining, the seam should be rolled with a steel or plastic roller in a direction perpendicular to the edge of the seam.

The adhesives used with the PVC primary test specimens are described as contact cements. The adhesive used with the neoprene buried test specimen could also be classified as contact cement.

All solvent cements can be used either in the field or in the factory, although with a thermoplastic material it would more likely be used in the field.

3.4.6.5 Vulcanizing adhesives

Vulcanizing adhesives achieve their strength from the crosslinking or vulcanization of the polymeric base. The vulcanization may be either a long or short-term operation and may occur under service conditions. Usually, a vulcanizing adhesive is a two-part system, one containing the polymer base, and the other the crosslinking agents. A complete system, as supplied by the manufacturer, includes a two-part cement, a rubber-base gum tape, and a lap sealant; it is designed for use in both the factory and the field.

3.4.6.6 Tapes

Tapes have been used to seam membrane lining materials in the field. They are made with pressure-sensitive adhesive applied either to both sides of a flexible substrate or to a flexible backing. The latter is removed once the tape has been placed on one of the surfaces to be joined. Tapes can be used to hold the sheetings in place while another seaming technique is used, or they can be used to provide the permanent bond.

Tapes have been used to seam polyethylene liners in the field; however, the use of tapes alone for making seams of liners for waste disposal facilities is not recommended.

3.4.6.7. Thermal techniques

A number of different techniques utilizing heat can be used in the factory or in the field. The surfaces to be seamed are melted and pressed together to form a homogeneous bond. One technique works by directing high temperature air between two sheets in an overlap seam followed by a pressure system. Another variant of heat seaming is dielectric seaming, which is a factory process involving the use of high-frequency dielectric equipment to generate heat and pressure on an overlap seam joint.

3.4.6.8 Welding or fusion methods

Some seaming of HDPE liners are being performed in the field with proprietary equiment which extrudes HDPE of the same composition as the liner either between the two sheetings being seamed or at the edge of one sheet to form a bead. Also, seaming equipment based upon heat guns has been devised in which coiled plastic welding rods are incorporated. The rod is fed to the seam area to form a welded seam. In the first welding procedure, a jet of hot air is injected into the overlap area to blow away debris and heat the area to be welded. Directly following the hot air, a ribbon of molten material identical to that of the sheet is injected into the overlap through an extruder nozzle. A roller moving behind the extruder nozzle presses the overlap together so the sheets will be fused together by the extruded ribbon of molten material. The result is a homogeneous weld that is immediately loadbearing. Welding can be carried out in ambient temperatures between 5°C to 35°C.

3.5 SPRAYED-ON LININGS

3.5.1 Introduction

Liners for disposal impoundments can potentially be formed in the field by spraying onto a prepared surface a liquid which then solidifies to form a continuous membrane. Such liners have been used in water control and impoundment, e.g. for canals, small reservoirs, and ponds. Most of the experience with this type of liner has been with air blown asphalt; however, a variety of new materials are becoming available which have been used in small water control installations. Sprayed-on liners are seam-free, but preparing them pinhole-free in the field may pose serious difficulties. Furthermore, most of the spray-on materials that have been considered are thermoplastic and are of low molecular weight, e.g. asphalt, and may interact adversely with many wastes. Some of the new materials that are being introduced are of high molecular weight or contain polymeric additives which improve their durability.

In this section, the following materials are discussed; airblown asphalt, emulsified asphalt, urethane modified asphalt, and rubber and plastics, in either liquid or latex form.

3.5.2 Air-blown Asphalt

Membranes of catalytically-blown asphalt are the most commonly used sprayed-on linings. The asphalts used in making these membrane linings have high softening points and are manufactured by blowing air through the molten asphalt at temperatures in excess of 500°F in the presence of a catalyst such as phosphorous pentoxide or ferric chloride. To prepare the membrane, the asphalt is sprayed on a prepared soil surface at a temperature of 400°F, at a pressure of 50 psi through a slot-type nozzle, and at a rate of 1.5 gal yd^{-2} (Bureau of Reclamation, 1963, p. 80). The finished liner is usually 0.25 inch thick (Bureau of Reclamation, 1963, p. 79), formed by two or more passes of the spray device and overlapping sections by one or two feet (Clark and Moyer, 1974). It can be placed during cold or wet weather, in large quantities, by mobile equipment (Bureau of Reclamation, 1963, p. 10). Sprayed-on membranes retain their tough flexible qualities indefinitely when properly covered and protected from mechanical damage (Asphalt Institute, 1976). The actual placing of the earth covers on a sprayed-on membrane may cause some damage to its integrity.

Studies have shown the addition of 3-5% rubber improves the properties of the asphalt by inducing greater resistance to flow, increased elasticity and toughness, decreased brittleness at low temperatures, and greater resistance to aging (Chan et al, 1978, p. 17).

Bituminous seals are used on asphalt concrete, portland cement concrete, soil asphalt, or soil cement linings to close pores, thus improving waterproofing or when there may be a reaction between the stored liquid and the lining. The two types of seals usually applied are:

a. An asphalt cement sprayed over the surface about one qt yd^{-2} to form a membrane about 0.04 in. thick.

b. An asphalt mastic containing 25 - 50% asphalt cement, the rest being a mineral filler, squeegeed on at 5 - 10 lb yd^{-2}.

Installation of sprayed-on asphaltic membranes is usually done on a subgrade which has been dragged and rolled to obtain a smooth surface. If there is an excessive number of irregular rocks and angular pieces, a fine sand or soil "padding" is necessary for good membrane support (Bureau of Reclamation, 1963, p. 81). Covering protects the membrane from most mechanical damage.

A special deep penetration formula of liquid cutback asphalt was applied over natural-on-site soil at a rate of two gal yd^{-2}. The seepage rate, in this case, was reduced from 15.9 to 6.14 ft^3 ft^{-2} yr^{-1} (Day, 1970, p. 20). Another formulation of cationic asphalt, incorporating white gasoline and water, penetrated 3/16 to 3/8 inch into the soil. This proved to be inadequate for complete sealing (Bureau of Reclamation, 1963, p. 115). A special cationic asphalt emulsion forms a highly impermeable seal at the soil interface through the attraction of the positively charged asphalt droplets to the negatively charged soil particles as the emulsion penetrates the substrate. As little as 15 fluid oz ft^{-2} results in almost zero seepage. This product has been used mainly in reservoirs and ponds (Wren, 1973).

Field data on a hot asphalt membrane lining in a canal lateral was obtained after 11 years of service. The seepage rate at this time was 0.08 $ft^3/ft^2/$ day. The seepage rate prior to placement of the liner was 9.9 ft^3/ft^2/day. Ninety percent of the aging occurred during the first four years of membrane service. A poor correlation was found between the 14-day laboratory aging test at 60°C and actual field aging. Geier (1968, p. 3) concluded that, if properly applied and covered, a buried hot applied asphalt membrane canal lining should last beyond 12 years.

Styron and Fry (1979) used an AC-40 grade asphalt cement as a lining material in tests with two flue gas desulfurization (FGD) sludges. A base of silty sand was compacted to six inches depth and cured at 78°F and 50% humidity for two to three days. The asphalt liner was then sprayed on the base at a rate of 0.75 gal yd^{-2}. After one year, under a pressure head of five feet of water, no liquid had passed through the liner. Specifications for AC-40 require a viscosity of 4000 ± 800 poises at 140°F (60°C) and a minimum penetration of 20. This asphalt requires temperatures of 300 - 400°F for spraying (Klym and Dodd, 1974).

Except for resistance to hydrocarbon solvents, oils, and fats, the chemical resistance of asphaltic liners is, in general, good. Asphaltic membranes are resistant to methyl and ethyl alcohols, glycols, mineral acids other than nitric acid (at moderate temperatures and concentrations), mineral salts, alkalis to about 30% concentration, and corrosive gases such as H_2S and SO_2. Asphaltic liners exhibit variable to poor performance when exposed to hydrogen halide vapors, but are essentially impermeable to water (Nat'l. Assn. Corr. Eng., 1966). Preparing pinhole-free membranes on large areas by spraying techniques, particularly when hot materials must be sprayed, poses a variety of problems which are discussed in Section 5.5.

3.5.3 Membranes of Emulsified Asphalt

Emulsions of asphalt in water can be sprayed at ambient temperatures (above freezing), to form continuous membranes of asphalt after breaking of the emulsion and evaporation of the water. The membranes are less tough and have lower softening points than membranes of hot applied catalytically-blown asphalt. Toughness and dimensional stability can be achieved by spraying asphalt emulsions onto a supporting fabric. Fabrics of woven jute, woven or nonwoven glass fiber, and nonwoven synthetic fibers have been used with various anionic or cationic asphalt emulsions to form linings for ponds and canals and as reinforcing patches under asphalt concrete overlays to prevent "reflection" of cracks in the old pavement beneath. Seams in the supporting fabric are often sewn with portable sewing machines after the fabric is placed (Phillips Petroleum, 1972).

3.5.4 Urethane Modified Asphalt

A urethane modified asphalt liner system is being marketed. It is generally spray applied, but may be squeegeed onto a prepared surface. A premix is combined with the activator, and sprayed on at a rate of two gallons per minute, covering about eight square yards per minute. The final membrane is generally recommended to have a thickness of 50 mil, usually obtained by applying one coat of 0.28 gal yd^{-2} on horizontal surfaces or two coats on vertical surfaces. The second coat may be applied about 15 minutes after the first coat. The membrane must cure for 24 hours before being put into service. This system has good UV stability and low temperature ductility, eliminating the need for a soil cover in most cases. The liner system is limited to a maximum of 140°F continuous exposure and is not recommended for prolonged exposure to hydrocarbon or organic solvents. It should be applied only to properly prepared surfaces. The surface must be clean and dry. Porous surfaces should be filled. Generally, a primer and a bonding agent are applied prior to the application of the actual membrane. The procedures for several base surfaces and the necessary precautions are provided by the manufacturer (Chevron, 1980).

3.5.5 Rubber and Plastic Latexes

Rubber and resin latexes have also been studied as spray-on liners. Gulf South Research Institute studied two synthetic latexes. The first was an experimental styrene polymer, which had a 50% solids content with a high concentration of wetting agents. The spray was allowed to soak into the soil and dry. The result was a fairly resilient film with good soil sealing capabilities. The second latex was an off-grade polyvinylidene chloride. It also had a 50% solids content and was used as a vapor barrier on air strips. It formed a film on the soil surface and was reported to provide a good seal at high pressures (Wren, 1973).

3.6 SOIL SEALANTS

The permeability of some soils can be significantly reduced by the application of various chemicals or latexes. They may be waterborne, mixed in place, spray applied, or injected below the soil surface (Gooding et al, 1967; Jones, 1971). Water borne or spray-on polymer soil sealants can reduce permeability of earth lined impoundments. However, the sealing effect is confined to the upper few centimeters and can be significantly diminished by the effects of wet-dry and/or freeze thaw cycles. Types of sealants include resinous polymer-diesel fuel mixtures, petroleum based emulsions, powdered polymers which form gels, and monovalent cationic salts (Bureau of Reclamation, 1963, p. 115). See Table 3-9 for a list of representative soil sealants.

Soil sealants utilizing monovalent cations, mainly sodium salts, chemically reduce the effective porosity of the soil for flow by replacing the multivalent cations in the clay structure. This exchange renders the clustered soil particles more easily dispersed (Willson, 1966). Sodium carbonate

TABLE 3-9. REPRESENTATIVE SOIL SEALANTS

Sealant	Application	Remarks
Cationic asphalt emulsion	Farm ponds	Requires approximately 19,000L/4,047 m^2 (5,000 gal/acre) dispersed in water.
Oil soluble polymers in diesel fuel	Fresh water	Injected beneath surface of water where seepage was occurring.
Sodium tetraphosphate	Sulfite liquor storage	Dispersant distributed in 15.2-cm (6-in.) layer of soil at 2.3 kg/9 m^2 (5 lb/100 ft^2). Careful compaction rendered soil impervious.
Sodium carbonate	Canals	Wet-dry cycles disrupt water barrier. Used 183 g (0.4 lb) of reagent/0.84 m^2 (yd^2) of soil.
Lignin derivatives gelled with alum	Desalination byproduct brine	1% lignin. Cost $3,400/4,047 m^2 (acre).
Carboxymethyl cellulose with alum	Desalination byproduct brine	0.2% CMC. Cost $2,250/4,047 m^2 (acre).
Petroleum emulsions	Desalination byproduct brine	4% additive. Cost $4,400/4,047 m^2 (acre).
Attapulgite clay	Desalination byproduct	2% Zeogel. Cost $1,000/4,047 m^2 (acre).
Liquid elastomeric polymer	Fresh water	Patent discloses several compositions, including polyurethane elastomers.

Source: Parks and Rosene, 1971.

applied at a rate of two lb yd^{-2} provided a seepage reduction of greater than 90% in Bureau of Reclamation tests. The seepage reduction was still 80% after removal of the top six inches of soil. Sodium pyrophosphate and sodium silicate are also potential soil sealants. Soil treated with sodium silicate and sulfuric acid prior to compaction showed a significant seepage reduction and is compatible with sulfuric acid bearing wastes (Clark and Moyer, 1974, p. 13).

Some powdered polymers can form gelatinous masses which tend to fill the soil voids, thus effecting a surface seal. Some early studies showed that this surface seal is easily damaged by a water spray, indicating that durability tests should be made when considering this type of liner (Willson, 1966). A powdered mixture of carboxymethyl cellulose and alum (0.25 CMC + 0.05% alum by wt of dry soil) was mixed with the soil and compacted to a six-inch thickness in one project. The seepage was reduced only slightly from 16 to 14 ft^3 ft^{-2} yr^{-1} (Day, 1970, p. 21). Soil sealants based on polymers are generally mixtures of swellable linear and crosslinked polymers of approximately the same molecular weight. The linear portion sorbs to the soil, forming a flexible network. The crosslinked polymer particles can flow, and thus can conform to and permeate the soil pores. The formulation depends on the application. The polymer is usually mixed in a low pH water/ acid solution and sprayed onto an unfilled site as a low viscosity slurry. The low pH allows the slurry to penetrate the surface and form a deeper seal.

Polymeric soil sealants may be applied as a dry blend which is mixed into the soil and compacted, sprayed on as a slurry, or dusted on as a powder. Highway construction equipment may be used for dry blending. Water hauling trucks equipped with centrifugal pumps, hoses, and adjustable fire nozzles have been successfully used to spray-apply polymer slurries. Any equipment suitable for dispersing a powder may be used for dusting with a polymer powder.

Dry blending forms the most effective seal and adds some structural strength to the impoundment. Other factors influencing the effectiveness of the seal are the degree of soil compaction and the composition of the impounded fluid.

The limitations of the polymer seals are: the polymer itself does not supply strength, the site must be compacted; exposure to salts, acids, and multivalent cations causes the polymers to shrink, increasing the permeability and decreasing the effectiveness of the seal (Parks and Rosene, 1971).

Uniroyal (1972) conducted a study to test the feasibility of using latex as a soil sealant to prevent seepage into subterranean abandoned mines. In general, the field tests confirmed laboratory findings that latex does reduce the permeability of the soil to water, but the latex is subject to damage by microbiological attack, frost, and vegetation.

3.7 CHEMICAL ABSORPTIVE LINERS

The use of chemical absorptive liners is a new and promising concept in the lining of waste disposal facilities. This type of liner functions primarily by removing pollutants from the liquid waste as it passes through the liner mass. Chan et al (1978) tested several clays and minerals, acidic and basic fly ash, bottom ash, activated alumina, and activated charcoal as potential chemical liners for calcium fluoride, metal finishing, and petroleum sludges. The tests were done under flow through conditions, mixing the sorbent with sand when necessary to achieve the required permeability. None of the substances alone adequately removed the hazardous or polluting compounds. However, combinations of sorbents, in a predetermined sequence, do satisfactorily remove contaminants. The type, sequence, and behavior of the sorbents varies with pH and the nature of the waste to be treated. For example, some materials remove certain metals or organics more effectively than others. The same sorbent, such as fly ash, may release ions in one pH range and absorb ions in another. Flow and nonflowing conditions also affect the absorption capacities of a material. This concept shows promise, but further testing is necessary under nonflow conditions with specific wastes to evaluate the effectiveness of various sorbents in applied situations (Chan et al,1978).

A test is underway of three chemisorptive lining materials, i.e. fly ash, limestone, and hydrous oxides of iron to assess the attenuation of heavy metals from two electroplating sludges (Phung et al, 1982). Based on the analyses of the leachates, results after about three years of exposure were inconclusive. The latter two materials were suggested by Fuller (1981) who indicated that they would be potentially useful as liners for metallic leachate constituents.

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CHAPTER 4

LINING MATERIALS IN SERVICE-TYPE ENVIRONMENTS

4.1 INTRODUCTION

In Chapter 2, different types of wastes that are or may be destined for land disposal are discussed with emphasis on their potential effects upon the integrity of liners. In Chapter 3, materials which might be used for lining waste storage and disposal impoundments are described and their characteristics discussed. In this chapter, we discuss the effects upon lining materials of exposure to different wastes and the interaction of liners and wastes that might exist in service-type environments. Some field service results are also reported.

The durability and service life of a given liner in a waste impoundment depends to a great extent upon the specific liquids which contact the liner from the time it is originally placed. The liquid emanating from waste can be highly complex at a given time and can continually change in composition with time even in a given impoundment. Consequently, an important consideration in the operation of a disposal facility is that measures should be taken to minimize the variation in the character of the waste, as there is no single lining material which can resist all wastes.

Potential liner materials can vary greatly in chemical composition from compacted soils and clays to highly crystalline polymeric materials which are highly chemically resistant and have very low permeability. Similarly, the wastes, as indicated in the discussion in Chapter 2, can vary from highly polar solvents, such as water, through highly nonpolar materials, such as lubricating oils and hydrocarbon solvents. Most wastes probably contain water as the principal carrier, though wastes of high organic content can also be encountered, such as those in drums. All compounds, either inorganic or organic, are, to a certain degree, soluble in water; consequently, contaminants or pollutants can be carried in the water. Also, many solvents can be totally miscible with water. The complexity of wastes can result in combined effects with respect to many of the liners.

Dissolved organic constituents in the leachate, even in minor amounts, can preferentially combine with organic liner materials and may, over extended periods of time, cause the failure of a liner based upon organic materials such as asphalt and polymeric materials. There are indications now that some organic waste liquids can also have major adverse effects on some soils and clays, as discussed later in this Chapter. Considerable information exists regarding water resistance of materials of which linings are made, regardless of whether they are soils, asphalts, or polymeric membranes.

Waste liquids, though most contain water and many dissolved ingredients, have different effects upon lining materials. The pollutants, which liners are designed to prevent from entering the groundwater at concentrations greater than allowed by regulation, may not themselves be aggressive toward liners. All constituents in a waste, as well as the liner composition, should be considered in assessing a liner material for a given impoundment.

Although there is much information on the effects of water on lining materials, no similar body of information exists on the effects on lining materials of chemicals and other liquids which might be found in the waste streams produced by various industries. On the other hand, considerable information is available on the effects of different chemicals and relatively simple mixtures of chemicals upon many polymeric materials that are used as containers, tank linings, pipe linings, and gaskets in direct contact with chemicals, solvents, and oils; however, these polymers are selected and compounded for the specific application. Consequently, the EPA undertook several research programs to study the effects of waste liquids and chemicals on lining materials:

Sanitary Landfill Leachate (Haxo, 1973-1981).

Hazardous Wastes (Haxo, 1975-1982).

Flue Gas Desulfurization Sludges (Styron and Fry, 1979).

State-of-the-art Study of Liners (Stewart, 1978).

Field Verification of Liners (Pacey and Haxo, 1980).

Effect of Organic Chemicals and Solvents on the Permeability of Clay Soils (Brown, Anderson, Green, ongoing).

4.2 THE EFFECTS OF WASTE LIQUIDS ON CLAY SOILS

4.2.1 Introduction

In Chapter 3, the general properties and characteristics of soils were discussed considering water as the liquid with which the soils would be in contact. Such properties as permeability, Atterberg limits, and strength are measured using water as the permeant or the test liquid. However, changing of the liquid or dissolving of either inorganic or organic constituents in the water can drastically change many of the properties of soils. The effect upon soil permeability is of particular importance if it is used as a liner for waste storage and impoundment facities.

Because permeability is the essential property that should be considered in the case of a soil liner, any alterations of a soil due to the presence of a waste-leachate should be identified. The most relevant characteristics which can alter soil flow properties are:

a. The dispersing/flocculating tendencies of the soil when contacted by the waste-liquid.

b. The alterations in the shrink/swell properties of the soil.

c. The change of pore-size distribution characteristics.

d. The dissolution/precipitation of chemical species, thus inducing an alteration of the proportion of soil volume available for flow.

e. The modification of the adsorption properties of the soils.

Interactions between clays or clay soils and waste leachates that may impact the permeability of the clay liner or stability of the clay sidewalls to a disposal site are discussed in this chapter. These are discussed under failure mechanisms. Results of a study by Brown and Anderson (1982) on the effects of pure organic chemicals and solvents on the permeability of several clay soils are presented.

4.2.2 Failure Mechanisms in Clay-Soil Liners

Failure mechanisms of clay liners are defined in this document as any interaction between waste liquids and compacted clay soil that can substantially increase the overall permeability of a clay liner and cause the liner not to meet the design requirements.

There are a variety of other mechanisms by which a clay-soil-lined landfill or waste impoundment can fail to prevent the escape of waste leachates. Seismic activity or subsidence can cause loss of the structural integrity of a liner. Tree roots, digging animals, or building activities may damage a landfill cover and allow the escape of volatile wastes. Various environmental conditions can affect the stability and strength of clay sidewall slopes, which may allow the lateral movement of waste leachates. There are still many unknowns with regard to waste containment. While there are a variety of failure mechanisms that can cause clay liners to leak excessively, this section deals with effects on the permeability of clay liners caused by interactions with waste liquids.

Increases in the permeability of a compacted clay liner due to waste liquids are usually associated with a shift in the pore size distribution toward more macropores. Climatological cycles (such as wetting and drying, freezing and thawing, percolating rainfall that dissolves soluble soil components, etc) are widely understood to be responsible for the development of large pores and permeability increases in undisturbed clay soils (Brewer, 1964; Brady, 1974). These natural processes can be greatly accelerated in the context of a remolded and compacted clay soil exposed to waste leachates.

4.2.2.1 Increase in permeability throughout the soil liner due to volume changes

Volume changes of a soil liner during service may occur if the equilibrium swell/shrink of the soil/water system is affected when water is replaced by the waste effluent.

Upon water replacement, the volume of individual clay particles changes, if the clay is non-kaolinitic. This happens because a clay particle is a porous micro-soil body, with a porosity fundamentally different from the one characteristic for the bulk soil. Due to its crystalline nature, the clay particle displays an orderly porosity, i.e. the space is represented by void regions, oriented parallel and intercalating the solid 2:1 matrix of the clay mineral. Thus, in a wet condition every 2:1 crystalline layer is separated from its two neighbors by two pore regions saturated with the particular liquid. The distance between the centers of two neighboring 2:1 crystalline layers separated by the interlayer liquid film is called "interlayer spacing" and is determined with x-ray diffraction analysis.

The interlayer spacing is a characteristic of a particular soil/liquid system depending on the clay mineralogy, the nature of the dominant adsorbed cation, and the properties of the saturating liquid.

Between two neighboring 2:1 layers, several forces operate. They have been traditionally discussed and grouped as attractive and repulsive forces.

The attractive forces are the van der Waals (fluctuating dipole bonds) and the London attracting energy forces. It is generally accepted that values of these attractive forces at a given distance from a 2:1 layer do not vary significantly with changes in environmental context, i.e. liquid characteristics.

The repulsive forces, on the other hand, are very sensitive to the environmental conditions and are strongly affected, particularly by the electrolyte concentrations, dielectric constant, and the dipole moment of the liquid present in the interlayer space.

The electrolyte concentration and the nature of the dominant cation in the liquid are very efficient in controlling the interlayer spacing, particularly in the case of some members of the smectite group clays. Thus, due to its large hydrated radius, Na-cation results in an almost unrestricted penetration of water inside the clay particle at which stage the water layers are several times the thickness of the 2:1 layer (Theng, 1973).

The effect of salt concentration on interlayer spacing of smectites was studied among others by Weiss (1958). While the distilled water and the 0.01N NaCl solution resulted in an infinite interlayer spacing, the 1,3, and 5N NaCl solutions yielded spacings of 1.92, 1.60, and less than 1.57 nm, respectively. At spacings below 1.5 nm, the repulsive forces are considered to be much smaller than the attractive forces (Yong and Warkentin, 1975) and the clay tends to flocculate.

Similar to the previously described situation when mineral species were dissolved in water, organic compounds and their concentrations also affect interlayer spacing. It has been shown by Greene-Kelly (1955) that the slightly basic aromatic compound, aniline, adsorbed with aromatic rings parallel to the clay surface at low concentrations (0.62 meq/gm clay) resulting in low interlayer spacing (1.42 nm), while a concentration of 0.91 meq/gm resulted in a larger spacing equal to 1.78 nm due to the positioning of aromatic rings perpendicular to the 2:1 clay layers.

It has been previously stated that the interlayer spacing is affected by the dielectric constant of the liquid present in the soil. The theory of dielectric constant has been thoroughly explained by Bockris and Reddy (1970). The dielectric constant of a liquid is its ability to transmit electrical charge. When the original water solution of the soil is replaced by an organic compound with a lower dielectric constant, the fluid film surrounding and present inside the clay particles must be thinner for the negative surface charge to be neutralized by the cations. Thus, the lower the dielectric constant of the replacing liquid, the smaller the interlayer spacing. According to the double-layer theory, the "half-distance", which is a measure of interlayer spacing, is proportional to the dielectric constant raised to the power 0.5.

Table 4-1 illustrates the relationship between dielectric constant and interlayer spacing. The presented data do not prove the validity of the square root relationship. It appears that the relationship is affected by other significant factors, among which are the dipole moment (Barshad, 1952), the nature of the adsorbed clay (Bissada et al, 1967), the degree of methyl substitution on the organic molecule (Olejnik et al, 1970), and ion-dipole interactions (Czarnecka and Gillott, 1980). All facts considered, however, the smaller the dielectric constant the smaller the interlayer spacing, which is illustrated by Barshad's (1952) results presented in Table 4-2.

TABLE 4-1. INTERLAYER SPACING OF CALCIUM SMECTITE AS A FUNCTION OF DIELECTRIC CONSTANT AND DIPOLE MOMENT[a]

Interlayer spacing, nm	Sorbed fluid	Dipole moment	Dielectric constant
0.99	Benzene	0	2.3
0.99	Paraffin	0	2.1
1.45	Butanol	1.6	17.7
1.70	Ethanol	1.7	25.0
1.71	Methanol	1.6	32.4
1.73	Methyl ethyl ketone	2.7	18.9
1.92	Water	1.8	78.5

Source: Barshad (1952).

[a] All samples were dehydrated at 250°C prior to immersion in the test fluid.

TABLE 4-2
INTERLAYER SPACING OF CALCIUM SMECTITE[a] IMMERSED IN LIQUIDS OF VARIOUS DIELECTRIC CONSTANTS[b]

Immersion liquid	Dielectric constant (25°C)	Interlayer spacing (nm)
100:0 Water:propanol	78.5	1.92
70:30 Water:propanol	57.7	1.88
40:60 Water:propanol	36.4	1.84
30:70 Water:propanol	30.7	1.77
20:80 Water:propanol	26.1	1.77
10:90 Water:propanol	22.7	1.52
0:100 Water:propanol	20.1	1.44
100:0 Water:glycerol	78.5	1.92
40:60 Water:glycerol	59.4	1.79
0:100 Water:glycerol	39.2	1.68

[a] Dehydrated at 250°C prior to immersion in liquid.

[b] Modified from Barshad (1952).

The interlayer spacing is an important clay characteristic because it controls the bulk volume change behavior of a soil. These bulk characteristics are identified in geotechnical investigation by determining the total swell, swelling pressure, shrinkage limit, and other soil characteristics which are closely related to swell and shrink, such as clay content, Atterberg Limits, or clay activity. When a clay soil compacted as a soil liner is permeated by a liquid with different charecteristics compared to water, changes in interlayer spacing occur. For example, if the water is replaced by an organic compound with a lower dielectric constant, the individual clay particles will contract as a result of a thinner interlayer spacing and thus an additional pore space will become available for clay particles to orient themselves, i.e. to flocculate. This regrouping and reorientation of clay particles may result in a decrease of void ratio, but most significantly should result in a change of the original pore-size distribution toward a distribution with larger pores. The consequence will be a greater permeability, but whether this permeability value will be greater than the designed value cannot be inferred a priori. This is the principal reason why testing of permeability of the soil to both water and the waste liquid is required, particularly when there is reason to believe that the waste liquid has a chemical composition or physical properties substantially different from water and thus differences in permeability are likely to occur.

The above described failure mechanism should normally occur throughout the whole soil liner where replacement by the waste fluid and the exposure time are of the same order of magnitude for different points in the liner.

In this discussion on volume-change characteristics of a soil, it was tacitly assumed that the greater the tendency of a soil to change its volume, the more drastic the changes in flow-properties can be expected. While this seems to be a logical conclusion, the quantification of such a statement is lacking at the present time, but it is certainly true for the case in which the original soil solution is changed in the long run by the waste-liquid. In the general swelling of a soil, an increase in void ratio should increase soil permeability since a larger proportion of the total soils volume is available for flow. In our particular situation, this may very well not be the case, because simultaneously with the volume increase, a change in pore size distribution will occur and with it a decrease in the median pore size of the soil. This latter effect can easily offset the volume increase tendency of the soil and thus result in a lower permeability of the soil.

Ideally, a soil specimen should be treated with the waste-liquid in a realistic way, its mechanical behavior observed, and any alterations in flow properties recorded. The final argument for using a particular soil as a liner (apart from its attenuating capacity) is its resistance to the flow of waste effluent into underlying, undisturbed soil.

4.2.2.2 Dissolution of clay

Dissolution of a clay liner can be brought about by an infiltrating chemical that dissolves the exposed surfaces of a pore or channel. Either organic or inorganic acids or bases may solubilize portions of the clay structure. Acids have been reported to solubilize aluminum, iron, alkali metals and alkaline earths while bases will dissolve silica (Grim, 1953). Since clay minerals contain both silica and aluminum in large quantities, they are susceptible to partial dissolution by either acids or bases.

Pask et al (1945) boiled several clay minerals in acid and found the percent solubilization of alumina was 3% from kaolinite, 11% from illite, and greater than 33% from montmorillonite. Grim (1968) found the solubility of clays in acid "varies with the nature of the acid, the acid concentration, the acid-to-clay ratio; the temperature and the duration of treatment." He also found that the action of an acid on clay was enhanced when the acid had an anion about the same size and geometry as a clay component. This would permit even weak acids, e.g. organic acids, to dissolve clays under some conditions.

Hurst (1970) found that the permeability of geologic formations could be increased by pumping in acetic or formic acid. Johansen et al. (1951) reported flow increases for water wells following their treatment with a solution containing citric acid. Grubbs et al. (1972) found acid waste as the probable causal agent in the permeability increase of carbonate-containing minerals. X-ray diffraction studies of the four clay minerals injected with acid waste showed them to be dissolved or completely altered. Diffraction peaks showed the most variability with montmorillonite clays.

Acidization is the name used for the process of permeability increase by acid mineral dissolution. This process is widely used to increase the permeability and hence the productivity of oil wells (Sinex, 1970).

An ever present source of organic acids in waste impoundments is anaerobic decomposition by-products. These include acetic, propionic, butyric, isobutyric and lactic acid. Anaerobic decomposition will yield the carboxylic acid derivatives of whatever organic fluids are placed in the impoundment.

Material that encrusts at the base of wells used to inject waste usually consists of calcium, magnesium and iron carbonates, along with imbedded sand and clay particles. In order to remove the carbonate compounds, they must be dissolved and then held in solution against precipitation forces. Dissolution is usually accomplished with a strong acid. At this point, calcium will reprecipitate (as calcium sulfate in the presence of sulfuric acid) unless it is chelated and removed by a flowing fluid. Chelating agents effective at preventing reprecipitation of various carbonates are citric acid, tartaric acid, and glycolic acid (Bur. Rec., 1977).

It is well known that strongly alkaline solutions can partially solubilize silica-containing soil constituents. Nutting (1943) showed even extremely dilute solutions of alkali to be effective at removing silica from smectites by dissolution from the crystal lattice.

4.2.2.3 Piping

Underseepage as the result of soil piping is an ever present danger in earthen dams. Mansur and Kauffman (1956) describe piping as "the active erosion... pressure and the concentration of seepage in localized channels." Jones (1978) found the early stages of piping development to be associated with vertical contrasts of the structure and permeability in soils. Soil piping was also associated with shifts in a soil pore size distribution toward macropores with no corresponding change in total porosity. A reactive fluid may enlarge the surface area of a pore by dissolution of the pore wall and by the dissolution of the soil matrix between two pores. While a fluid's reactivity is reduced by its action on the pore wall, the size increase of the pore will increase the turbulent character of the flow inside the pore and consequently the erosion power of the moving fluid. In this manner, any variability in the pore size distribution of a clay liner may be magnified with time. Schechter and Gridley (1969) found that wormhole formation was the result of a reactive fluid's preferential flow in larger pores. He went on to say that a quasi-equilibrium is reached where further growth in a pore is limited by the rate of diffusion of the reactive fluid.

Seepage by reservoir water into dams has been reported to have caused dispersive piping and eventual tunneling all the way through earth dams. Tunneling was reported to occur in soils with a local permeability of 1×10^{-5} cm s^{-1}.

Differential solution and subsequent leaching, especially with calcareous sediments, was reported to result in the formation of channels, sink holes and cavities (Mitchell, 1976). In this respect dissolution seems to be in some circumstances a precondition for piping.

Cedergren (1967) reported that differential leaching of limestone, gypsum and other water soluble mineral components can lead to development of solution channels that get larger with time and substantially increase permeability. He warned not to underestimate the importance of minor soil and geologic details on the permeability of soil formations as they cause the majority of failures in dams, reservoirs and other hydraulic structures.

Cedergren (1967) concluded that most failures caused by seepage can be placed in two categories:

a. Those that are caused by soil particles migrating to an escape exit, causing piping and erosional failures; and

b. Those caused by uncontrolled seepage patterns which lead to saturation, internal flooding, and excessive seepage.

Crouch (1978) found that so called tunnels, tunnel-gullies, or pseudokarsts will develop in dispersive soils where the soil-colloid bond strengths are low compared to the energy of water flowing through the soil. He found dispersive soils or those with low structural stability have been associated with tunnel erosion throughout the world. Other factors found to be related to tunnel erosion were ESP (exchangeable sodium percentage), soil cracks, low permeability, and hydraulic gradients.

In a study of the variables affecting piping, Landau and Altschaeffl (1977) noted a strong interaction between the chemical composition of the eroding water and compaction water content. Ion concentration seemed to have little effect on soil piping susceptibility for mixed illitic and kaolinitic clay loam compacted dry of optimum. For the same soil compacted wet of optimum, soil piping susceptibility was highly related to ion concentration in the eroding water. When low ion concentration eroding water is combined with wet-of-optimum compaction, Landau and Altschaeffl (1977) reported low resistance to internal erosion.

Piping involves the slaking of soil particles. Slaking is defined as the disintegration of unconfined soil samples when submerged in a fluid. Moriwaki and Mitchell (1977) investigated the dispersive slaking of sodium and calcium saturated kaolinite, illite, and montmorillonite. All the clays slaked by dispersion when saturated with sodium with the process proceeding faster with sodium kaolinite and sodium illite. Sodium illite swelled slightly while dispersion of sodium montmorillonite was preceded by extensive swelling. Sodium kaolinite underwent no visible swelling while dispersing. For the calcium saturated clays, illite dispersed much more slowly while the rate of dispersion increased for kaolinite and montmorillonite. Calcium kaolinite was thought to disperse faster because of its higher permeability relative to sodium kaolinite. Sodium montmorillonite was thought to disperse slowly because the large degree of swelling it underwent would lower permeability, thus slowing water entry and retarding dispersion.

Compaction has been shown to decrease the electrolyte content of expelled interlayer water (Rosenbaum, 1976). Such a lowering of fluid electrolyte concentrations in sodium-saturated clays may cause substantial swelling and dispersion (Hardcastle and Mitchell, 1974). This dispersion causes particle migrations. If there are fluid conducting pores large enough to transport these dispersed clay particles, permeability increases and soil piping may result (Aitchison and Wood, 1965).

It is important to note that piping would initiate on the underside of a clay liner where clay particles could migrate into a substrata with larger pore diameters. The soil pipe would then progress upward through the clay liner until it finds an opening into the waste impoundment. Clay particles have been shown to migrate through porous media containing less than 15% clay (Hardcastle and Mitchell, 1974). Consequently, clay liners underlain by soils containing less than 15% clay may be susceptible to soil piping.

Four laboratory tests for the determination of soil susceptibility to dispersive erosion have been developed by the U.S. Soil Conservation Service. A major conclusion of a recent symposium on soil piping was that these four tests should be performed on soils where piping would cause unacceptable damage (Sherard and Decker, 1977). The four tests are the pinhole test, a test of dissolved salts in the pore water, the SCS dipsersion test, and the crumb test. For the test methods and extensive test data see ASTM Special Technical Publication No. 623.

4.2.2.4 Slope stability

When the topography of the waste-disposal site is flat, soil strength characteristics are of little consequence. However, environmental and economic criteria often prevail in the process of choosing a waste disposal site; environmentally, such a site should be placed as far away as possible from highly populated areas, and since these are mostly flat areas; the disposal sites will be pushed into hilly dissected topographical regions; economically, a hilly region has its advantages in the sense that placing a waste in a ravine, for instance, may involve generally less earth work and result in a higher efficiency of waste-storage per unit disposal area. Consequently, in many situations, the waste-disposal site floor will be sloping and so will the soil liner. A similar situation occurs even when the floor of the waste-disposal site is flat, but the waste is buried under the ground surface. In this case the waste-disposal "site" will have a trapezoidal cross section with lateral slopes. The consolidation of the waste during the storage time can result in uncovering of slopes, relief of lateral pressures, and possibly an unstable condition. For these situations, an investigation of stress-strain and strength properties of the soil has to be conducted. The difficulties associated with the analysis of slope stability are not associated with the usual difficulty in determining properly the cohesional and frictional characteristics of the soil, but rather with a proper estimation of the characteristic hydrology of the site under operation condition; in other words, changes in the hydrology have to be estimated, average and "worst" patterns have to be identified, and all information integrated into a factor of safety using pertinent methods of analysis.

Although slope stability considerations are important, we believe that due to the vast amount of available information on this subject, the design of the slope can be done in such a way that a factor of safety larger than 1.4 - 1.5 can be generated. The problem is slightly more complicated when there is a partial replacement of soil water by waste-leachate; the design of the slope cannot be done without considering this factor.

In Section 5.2.2.5, the influence of different factors upon soil strength are presented and suggestions are made regarding the testing of the soils for strength.

The failure of a sloped soil liner can occur as a slippage of the whole compacted layer over the undisturbed soil or bedrock. Another mechanism is the creep of very cohesive saturated clays; by this mechanism tension can be generated in a slope and cracks perpendicular to the slope can enhance failure.

We define all these conditions as "failure", since they will lead to changes in the integrity of the soil liner with adverse effects upon bulk soil flow-properties.

4.2.2.5 Miscellaneous

There are a variety of situations that may increase the permeability of clay liners other than those discussed above. The phenomena causing the permeability increase may not be fully understood, but they are presented here for their possible usefulness in future research.

Miller et al (1975) found that the permeability of a soil increased as water flushed out an earlier application of surfactant.

Grubbs et al (1973) found that methyl alcohol increased the permeability of a core previously injected with oil-base wastes. He also noted the use of solvents, organic acids, surfactants, alcohols, and emulsion breakers for permeability enhancement in deep well injection operations.

Letey et al (1962) observed for water-repellent soils an increase in the infiltration rate with time. He felt this was due to the progressive neutralization of the soils' water repellency as the depth of infiltration increased. In a later study, Miller et al (1975) found that permeability increases with time if there is a substance in the soil that would dissolve into the water and decrease its surface tension.

Watson (1968) found surfactants acted to stabilize soils against dispersion and swelling, thereby preventing a decrease in permeability values at certain surfactant concentrations.

Wolstenholme (1977) stated that solvents of low viscosity are "by their very nature" leachable and able to extract organic components from otherwise dry waste. Low viscosity would significantly increase a fluid's permeability according to Darcy's Law.

4.2.3 Laboratory Study of the Effects of Different Organic Liquids on Soil Permeability

4.2.3.1 Introduction

Liquids emanating from wastes were reviewed in Chapter 2. From the standpoint of soils, they were divided into water and four classes of liquids: acidic, basic, neutral polar, and neutral nonpolar. In this subsection, data are presented on the effects organic liquids have on the permeability of clay soil liners for waste storage and disposal facities. Additionally, the effects of water on the permeability of clay liners previously permeated by various organic liquids are discussed.

Some uncertainty exists as to whether clay soil liners would be saturated and hence permeated by percolating water before the leachate from the disposed waste enters the liner. The degree of clay soil liner presaturation is dependent on the nature of the disposal facility, the climatic context of the disposal site, and the design criteria for the liner. If the disposal facility remains open after construction and during waste placement, it would act as a bathtub, catching any precipitation that might occur. Some disposal facilities may maintain clay soil liners in an unsaturated state, such as those in drier climates prevalent in parts of western and central United States or that have an effective leachate removal system; however, most industrial landfills are located in relatively wet climates, such as the Gulf Coast, Great Lakes, Northwest, Northeast, and Southeast regions of the United States (EPA 1980a; EPA 1980b). These wetter climates would probably maintain any buried clay soil near saturation. Another factor that would determine if a clay liner is presaturated would be the design criteria set out by the manufacturer of a processed clay if it is a bentonite liner. In general, design criteria for bentonite liners suggest the complete presaturation of the clay to optimize swelling of the clay, thereby obtaining the tightest seal.

The testing of the permeability of clay soils which are candidates for lining of hazardous waste landfills and surface impoundments has been performed in the past using water or a standard aqueous permeant such as 0.01 N calcium sulfate solution. In view of the concern of the effects of various liquids which contain dissolved organic or inorganic constituents and of organic solvents upon the permeability of clayey soils, Brown and Anderson (1982) conducted an investigation into the effects of four classes of pure organic liquids upon the permeability of four selected clay soils. Based upon laboratory permeameter testing, results to date show that clays that are satisfactory, as judged by water permeability testing under standard ASTM test methods, increase drastically in permeability when tested with various pure organic chemicals. These clay soils underwent large permeability increases when permeated with basic neutral polar, neutral nonpolar, or organic liquids, and showed potential for substantial permeability increases when exposed to concentrated organic acids.

The results of this study indicate the need to test the permeability of potential clay liners with the organic liquid that the liner may be expected to impound. The results of this work is summarized in the following subsections (Brown and Anderson, 1982).

4.2.3.2 Materials and methods

Four native clay soils, having different mineralogical chemical properties, were selected for this study. Two of the soils contained predominantly smectitic clay minerals having different chemical properties. The other two soils contained predominantly kaolinitic and illitic clay minerals. Each soil was characterized by the following:

- A permeability less than 10^{-7} cm s^{-1} when compacted at optimum water content.
- A geographic extent of at least one million hectares.
- Deposits thick enough to permit economic excavation for use as clay-soil liners.
- A minimum content of 35% by weight of clay minerals.

The general properties of these four clay soils are given in Table 4-3.

TABLE 4-3. DESCRIPTIONS OF THE FOUR CLAY SOILS USED IN STUDY

Clay soil description	Noncalcareous smectite	Calcareous smecite	Mixed cation kaolinite	Mixed cation illite
% Sand (> 50μm)	35-37	7-8	39-41	14-15
% Silt (50-2.0μm)	26-28	42-44	17-18	38-39
% Clay (<2.0μm)	36-38	48-50	42	47
Predominant clay minerals[a]	1.Smectite 2.Mica 3.Kaolinite	1.Smectite 2.Kaolinite	1.Kaolinite 2.Mica	1.Illite 2.Smectite
Shrink-swell potential	Very high	Very high	Moderate	Moderate
Corrosivity (steel)	High	High	High	(b)
Cation exchange capacity (meq/100gms)	24.2	36.8	8.6	18.3
Total alkalinity (meq/100gms)	3.3	129.2	0.8	4.2

[a] In order of descending quantity in the soil.
[b] Not determined.

In preparing the soils for test, the clay soils were first broken into golf ball-sized clods and then air dried. Each soil was then ground sufficiency to pass ASTM No. 4 sieve (4.7 mm) and then stored at room temperature in large drums. The methods used for determining soil properties are described by Black (1965), except for moisture density relationships where ASTM test methods were used.

General and detailed information on the four soils can be obtained in the report by Brown and Anderson (1982). They report soil series and order, location, geographically and within the solum, and the parent material from which each soil was derived. Also, they report grain size distribution and mineralogy, physical properties including permeability, and chemical properties.

The organic liquids included four classes:

- Organic acids.
- Organic bases.
- Neutral polar organic liquids.
- Neutral nonpolar organic liquids.

Water was also included in the testing as a reference liquid. The organic liquids used in this study were all reagent grades. This is in contrast to waste liquids which are normally a mixture of liquids combined with organic and inorganic solutes. Also, the waste liquids often contain suspended solids that could clog or coat pores. Relevant chemical and physical properties of these test liquids are presented in Table 4-4.

Water (0.01 N calcium sulfate) was used as a control liquid or permeant to establish baseline permeability of each soil specimen. The calcium salt was selected due to its stabilizing effect on permeability. This particular concentration was used because it approximates the salt concentration typically found in soils. Additional details of these liquids can be found in the report by Anderson et al (1982).

The procedure used in the test is described in Appendix III-C, "Test Method for the Permeability of Compacted Clay Soils (Constant elevated pressure methods)". The soils were compacted to 90% Proctor in standard permeameters. The permeability testing used constant elevated pressures of either 10 or 60 psi. The tests were started using 0.01 N calcium sulfate solution and, once steady values were obtained, the solution was replaced with the organic liquid to be tested. The pressure used with the illite and kaolinitic soils was 10 psi, and 60 psi was used with the two smectitic soils.

4.2.3.3. Experimental results

Water. Permeability of four compacted clay soils to a standard test aqueous liquid or permeant (0.01N $CaSO_4$) were examined by Anderson et al (1982) and are presented in Figure 4-1. Permeability values of noncalcareous smectite and mixed cation kaolinite soils were essentially constant during passage of

TABLE 4-4. SELECTED PROPERTIES OF THE ORGANIC TEST LIQUIDS[a]

Solvents: Organic fluid	Solvents: Name	Density at 20°C (gm/cm^3)	Viscosity at 20°C (centipoise)	Dielectric constant at 20°C	Water solubility at 20°C (gm/l)	Dipole moment (debyes)
Acid, carboxylic	Acetic acid (glacial)	1.05	1.28	6.2	∞	1.04
Base, aromatic amine	Aniline	1.02	4.40	6.9	34.0	1.55
Neutral polar, alcohol	Methanol	0.79	0.54	31.2	∞	1.66
Neutral polar, ketone	Acetone	0.79	0.33	21.4	∞	2.74
Neutral polar glycol	Ethylene glycol	1.11	21.0	38.7	∞	2.28
Neutral non-polar, alkane	Heptane	0.68	0.41	2.0	0.003	0.0
Neutral non-polar, alkyl-benzene	Xylene	0.87	0.81	2.4	0.20	0.40
Water	...	0.98	1.0	80.4	∞	1.83

[a] For additional data on these organic liquids, see Table 2-2.

approximately two pore volumes of the standard permeant. In contrast, permeability of calcareous smectite decreased slowly while that of the mixed cation illite increased slowly; both changes were, however, small.

Relative permeability values for the four clay soils to water are consistent with values typical for those clay types. Kaolinite exhibited the highest, noncalcareous (partially sodium saturated) smectite showed the lowest, and calcareous (calcium saturated) smectite and mixed cation illite had intermediate permeabilities.

After passage of two pore volumes of standard aqueous permeant, the four clay soils exhibited no visible aggregation and appeared to have retained their initially massive structure. In addition, the surface of the soils showed no signs of pore enlargements.

Traditionally, permeability tests on prospective clay soil liners for hazardous waste landfills and surface impoundments have used only standard aqueous solution, such as 0.01N $CaSO_4$ or $CaCl_2$, as the permeant liquid. All four of the clay soils shown in Figure 4-1, if only tested with the standard permeant, would qualify as adequate for lining hazardous waste disposal facilities on the basis of their low permeabilities of less than 1×10^{-7} cm s^{-1}.

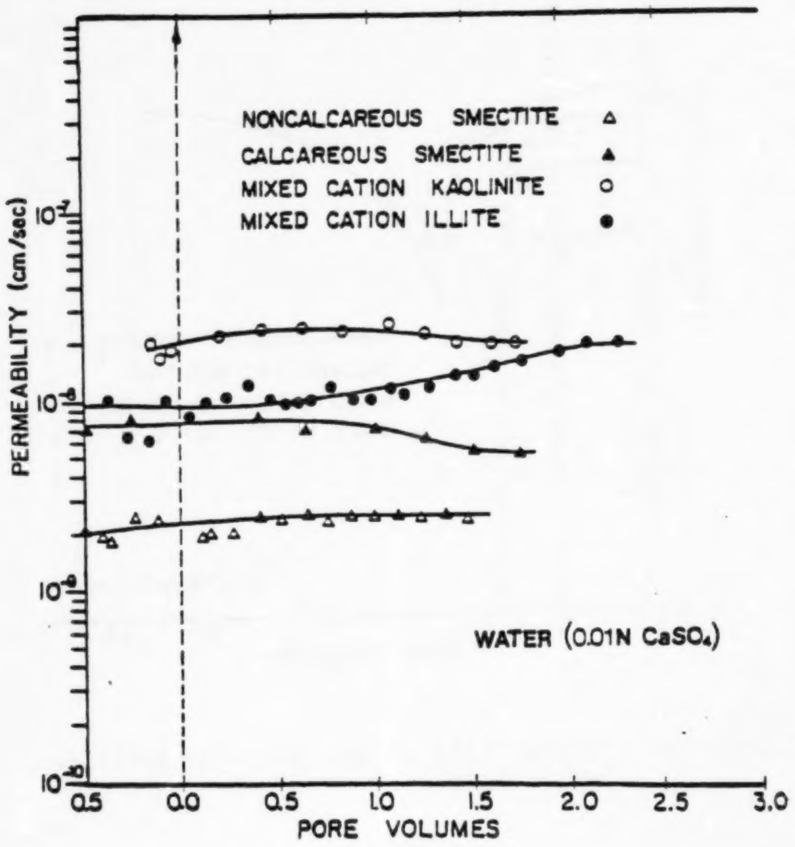

Figure 4-1. Permeability of the four clay soils to standard aqueous permeant (0.01N $CaSO_4$).

Organic Acids - Acetic Acid. Organic acids are rarely the predominant liquid in the leachate generated by a waste. They would usually be present, however, as one of the dissolved components in whatever liquids leached out of waste disposed of in an anaerobic environment such as is common in landfills and surface impoundments. Effects of dilute solutions of organic acids on the permeability of clay liners are discussed in subsection 4.2.2.

Permeabilities of four compacted clay soils to concentrated (glacial) acetic acid were measured by Anderson et al (1982) and are presented in Figure 4-2. Baseline permeability values for the four clay soils were established with the standard permeant (0.01N $CaSO_4$) and are shown to the left of the dotted line. All four soils showed initial decreases in permeability when the permeant was changed from the standard to acetic acid.

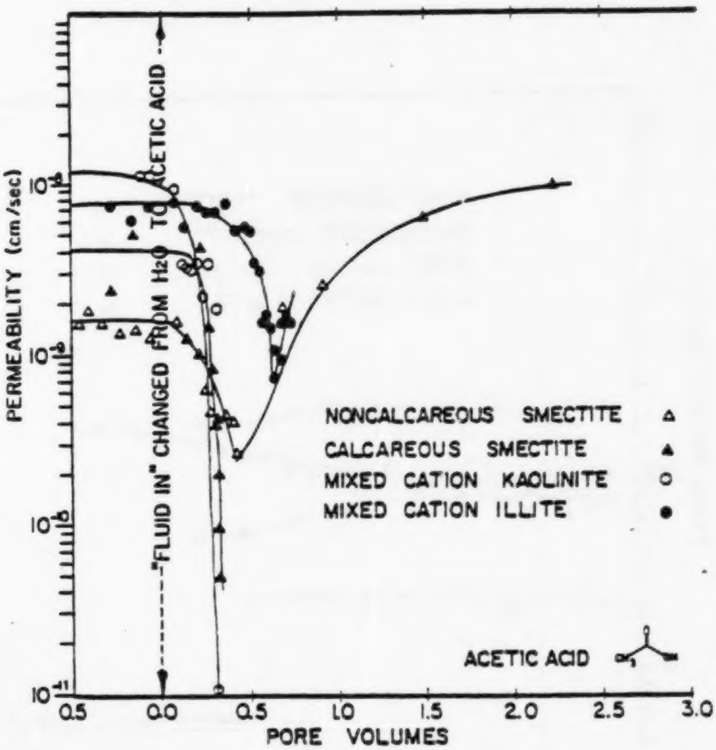

Figure 4-2. Permeability of the four clay soils to glacial acetic acid.

Significant amounts of soil piping occurred in these soils, as indicated by the soil particles deposited on the bottom of collection bottles. In addition, effluent from these soils was usually tinted (red, creamy, or black) indicating that soil components were dissolved by the acid. Initial decreases in permeability may be due to partial dissolution and subsequent migration of soil particles. These migrating particle fragments may have lodged in the liquid conducting pores, thus decreasing the cross-sectional area available for liquid flow.

Two of the soils treated with acetic acid (calcareous smectite and mixed cation kaolinite) decreased continuously in permeability throughout the test period. After passage of approximately 20% of a pore volume, the acid treated kaolinitic clay generated a dark red effluent with the odor of acetic acid. The color was probably due to dissolution of iron oxides which comprise about 13% of the solids in the kaolinitic clay soil. The acid-treated calcareous smectite began passing cream-colored foamy effluent after passage of about

28% of a pore volume. Since the solid fraction of this clay soil is approximately 33% calcium carbonate, the largest portion of the creamy material probably was dissolved calcium, and the foam the result of CO_2 liberation from the dissolved carbonates.

Both noncalcareous smectite and the mixed cation illite eventually increased in permeability after the initial decreases, but the increases did not begin until passage of 39% and 62% of a pore volume, respectively. Effluent from the noncalcareous smectitic clay contained soil particles and a black ash, while effluent from the illitic soil contained red-tinted soil particles that became increasingly darker as more effluent passed. Permeability increases with both of these soils were thought to be due to progressive soil piping that eventually cleared initially clogged pores.

In light of the across-the-board piping that occurred with the acid treated clays, any liquid (such as strong acids and bases) capable of dissolving clay liner components could potentially cause increases in the permeability of the liner. Anderson et al (1982) suggested that neutralization of acids and bases prior to their disposal may be the best safeguard against failure of a clay soil liner.

The density to viscosity ratio of acetic acid (0.82) implies that permeability should decrease approximately 18% from the value obtained with the standard permeant. However, the large permeability decreases and subsequent increases (in two of the soils) indicate that soil piping was the predominant influence responsible for permeability changes.

Organic Bases - Aniline. Permeabilities and breakthrough curves for four clay soils permeated by a weak organic base (aniline) were determined by Anderson et al (1982) and are given in Figure 4-3. Baseline permeability values were established for the soils with a standard permeant (0.01N $CaSO_4$) and are to the left of the dotted line in Figure 4-3. All four clay soils showed significant permeability increases when permeated by the weak organic base.

Both noncalcareous smectite and mixed cation illite had breakthrough of aniline with concurrent permeability increases at lower pore volume values (<0.5) than the other two clay soils. The permeability of the noncalcareous smectite appeared to reach a constant value just above 1 x 10-7 cm sec^{-1}.

Permeability rose above 1 x 10^{-7} cm sec^{-1} and aniline broke through the kaolinitic soil after passage of one pore volume. Only the calcareous smectite clay maintained a permeability value below 1 x 10^{-7} cm sec^{-1}. Its permeability increased rapidly at first, but decreased substantially concurrent with aniline breakthrough. After the permeability decrease, this soil exhibited a slow but steady permeability increase.

There were no signs of migrating soil particles in any effluent samples collected from the four aniline-treated specimens. Apparently, aniline is too weak a base to cause significant dissolution of clay soil components. However, examination of the cores subsequent to the permeability tests indicated that the organic base caused extensive structural changes in the upper half of the soils. The massive structure of the four soils after treatment with the standard permeant was altered by aniline into an aggregated structure characterized by visible pores and cracks in the surface of the soils.

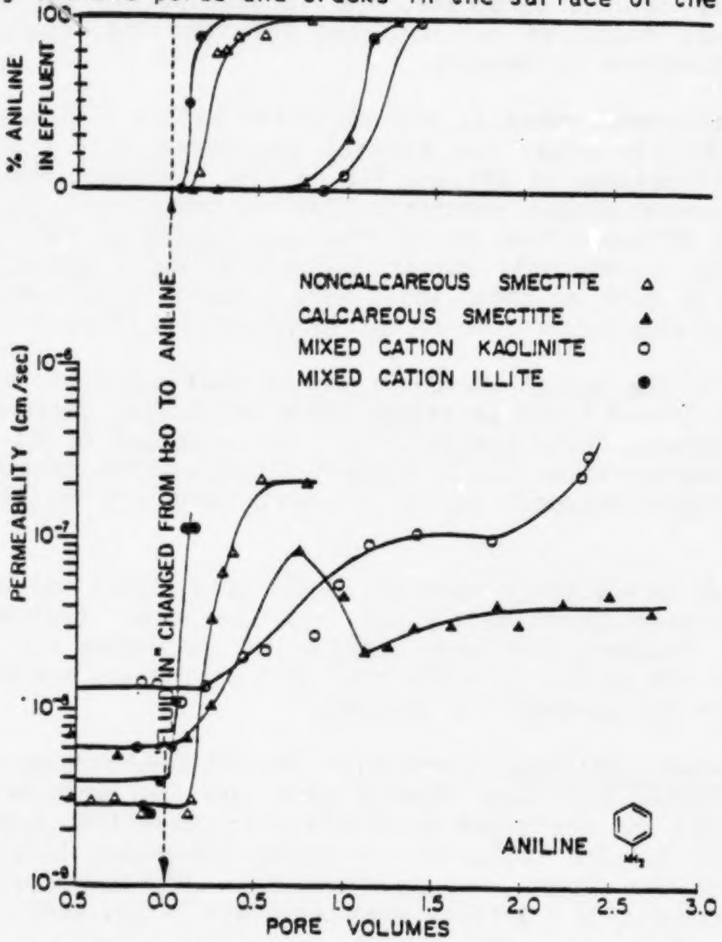

Figure 4-3. Permeability and breakthrough curves of the four clay soils treated with aniline.

According to the equation for intrinsic permeability, a permeant with density and viscosity of aniline should result in soil permeability 77% lower than that obtained with water, e.g. the standard permeant. However, the four soils that were tested underwent increases in permeability between 100% and 200% when permeated with aniline. It appears that the predominant factor affecting permeability is the ability of aniline to alter the structural arrangement of particles making up clay soils.

Neutral Polar Organics - Acetone. Many common industrial solvents can be described as neutral and polar such as ethylene glycol, acetone, and methanol. Polarity generally indicates that a chemical has a relatively high water solubility and therefore polar organic liquids may be present in aqueous leachates in concentrations ranging from parts per billion to double digit percentages. In this subsection, data are presented where a polar organic chemical is the predominant liquid phase Figure 4-4).

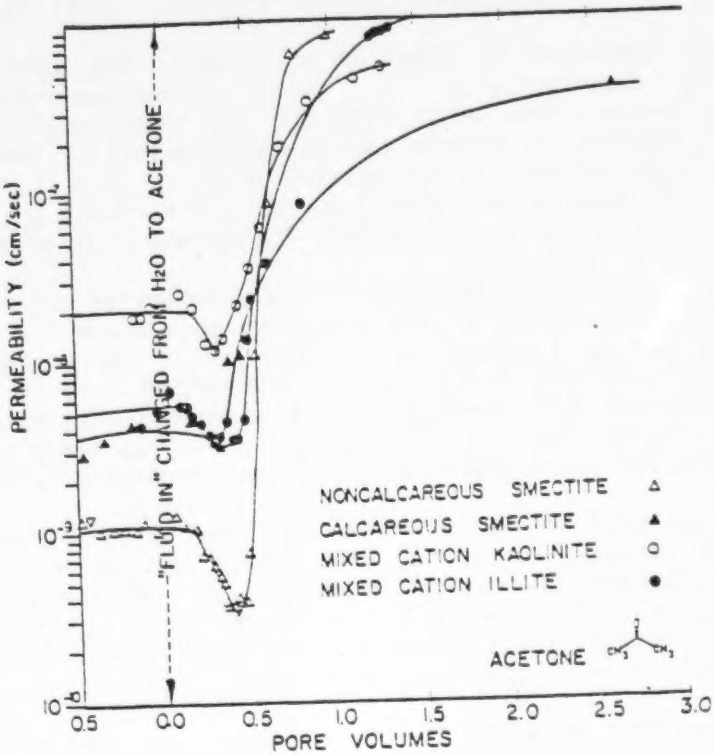

Figure 4-4. Permeability of the four clay soils to acetone.

It is interesting to note that all the clay soils that were permeated with acetone initially decreased in permeability. These decreases continued until passage of approximately 0.5 pore volume. During passage of the next 0.5 pore volume, however, the permeability of the soils underwent large increases. One possible explanation for this sequence of changes is as follows:

1. The higher dipole moment of acetone caused an initial increase in the interlayer spacing between adjacent clay particles, as compared with water, i.e. the standard permeant.

2. As more acetone passed through the soil specimens, more water layers were removed from clay surfaces. Due to its larger molecular weight, however, fewer acetone layers were adsorbed than were adsorbed when water was the only liquid present. This resulted in a larger effective cross-sectional area available for fluid flow.

While acetone can displace water from clay surfaces, due to its higher dipole moment, it cannot form as many adsorbed layers as water due to its higher molecular weight (Anderson, 1981).

Examination of the soil after acetone permeation showed extensive shrinkage and cracking. Such shrinkage is thought to be associated with dehydration, indicating that acetone extracts water from soil particle surfaces.

In a study conducted by Green et al (1981), the same initial decrease in permeability occurred with three other acetone-permeated clay soils. Apparently, however, the tests were not run long enough to pass a sufficient volume of permeant to observe the large permeability increases that occurred above 0.5 pore volume in the present study. This further illustrates the importance of passing at least one full pore volume of a waste leachate to determine how the liquid will affect the permeability of a clay liner.

Neutral Polar Organics - Methanol. Permeabilities of four compacted clay soils permeated by methanol and a breakthrough curve for an illitic clay soil were determined by Anderson et al (1982) with the standard aqueous permeant (0.01N $CaSO_4$) and are to the left of the dotted line in Figure 4-5. As with acetone-permeated soil specimens, soil permeated with methanol reached permeabilities greater than 1×10^{-7} cm sec^{-1}. Unlike soils treated with acetone, methanol-treated soils underwent no initial permeability decrease.

Increased methanol in the effluent from the illitic clay soil paralleled an increase in permeability of the soil. After passage of 1.5 pore volumes, the hydraulic gradient was reduced from 61.1 to 1.85 and another pore volume of methanol passed (Figure 4-6). After an initial decrease, permeability of the soil steadily increased at the lower hydraulic gradient to a value greater than 1×10^{-5} cm s^{-1}.

No particles were detected in the effluent from the soil specimen permeated with methanol; therefore, soil piping was discounted as a mechanism for the observed increase in effluent flow. If these increases were due solely to the 1.46 density to viscosity ratio, permeability of the soils would have leveled at values 150% of those obtained with water. Instead, the soils showed steady permeability increases to values greater than 1,000% (kaolinitic soil) and 10,000% (illitic and smectitic soils) of permeability values with the standard permeant.

Examination of methanol-permeated soil specimens taken from the permeameter revealed development of large pores and cracks visible on the soil surface (Anderson et al, 1982). The lower dielectric constant of methanol compared with water was considered to have caused a decrease in interlayer spacing of the clay minerals present in the soils, thereby promoting the structural changes. Table 4-2 shows the trend relating dielectric constant to interlayer spacing for propanol, another low molecular weight alcohol, in various concentrations of water. In the case of propanol-permeated clay, both the dielectric constant of the permeant and the interlayer spacing of the clay decreased as the percentage of propanol in the permeant increased.

Neutral nonpolar organics. Neutral nonpolar organic liquids are probably the largest class of nonaqueous waste liquids. Most waste oils and a large part of discarded industrial solvents can be characterized as nonpolar. Common nonpolar industrial solvents include aromatic compounds, such as xylene and benzene, and aliphatic compounds, such as heptane. In this subsection, data

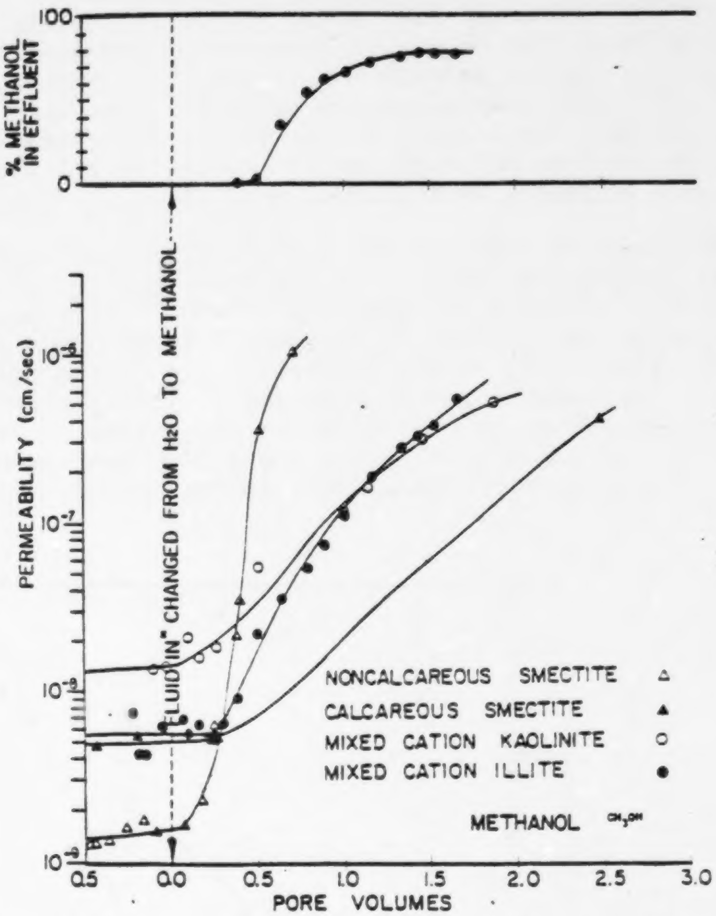

Figure 4-5. Permeability of the four clay soils to methanol and the breakthrough curve for the methanol-treated mixed cation illitic clay soil.

are presented where a nonpolar organic chemical is the predominant liquid phase.

Replacement of a polar permeant, such as water, by a nonpolar one was found to cause permeability increases of between 10% and 30% in compacted kaolinitic clay beds (Michaels and Lin, 1954). It was concluded that the most important factor controlling the permeability was the degree of dispersion or disaggregation existing in the original permeant.

Xylene--Permeabilities and breakthrough curves for four compacted clay soils permeated by xylene were evaluated by Anderson et al (1982) and are given in Figure 4-7. Baseline permeability values for the soil specimens were established with the permeant (0.01N $CaSO_4$) as shown to the left of the dotted line in Figure 4-7. Xylene-permeated soils showed rapid increases in permeability followed by nearly constant permeabilities, roughly two orders of magnitude greater than their permeabilities to water, i.e. the standard permeant.

Permeability increases due to the ratio of density to viscosity of xylene (1.07) accounts for only a 7% increase in permeability over values obtained with water. Since permeability increases averaged 10,000% (two orders of magnitude), other mechanisms are obviously involved. An indication of these mechanisms was the structural changes in the xylene-permeated soils, illustrated by massive structure before permeation and blocky structure after the soils were permeated with xylene.

Another study by Green et al (1981) noted that neutral nonpolar compounds, such as xylene, may greatly increase permeability of compacted clay soils by causing the formation of shrinkage cracks. This study, however, listed the "equilibrium coefficient of permeability" for the xylene-permeated soils as the low permeability values obtained prior to the formation of the shrinkage cracks. The authors then plotted these artificially low permeability values for the neutral nonpolar liquids vs dielectric constant and arrived at the following conclusion: All clay soils are more permeable to water than to organic solvents, which is contrary to the results of the work of Anderson and Brown.

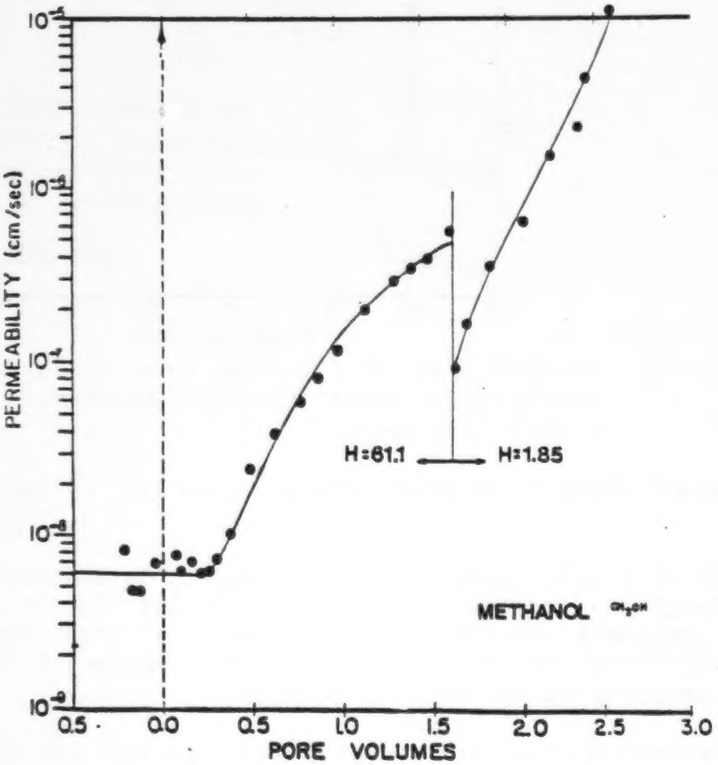

Figure 4-6. Permeability of the mixed cation illitic clay soil to methanol at two hydraulic gradients. Permeant used to the left of the dotted line is 0.01N aqueous solution of $CaSO_4$.

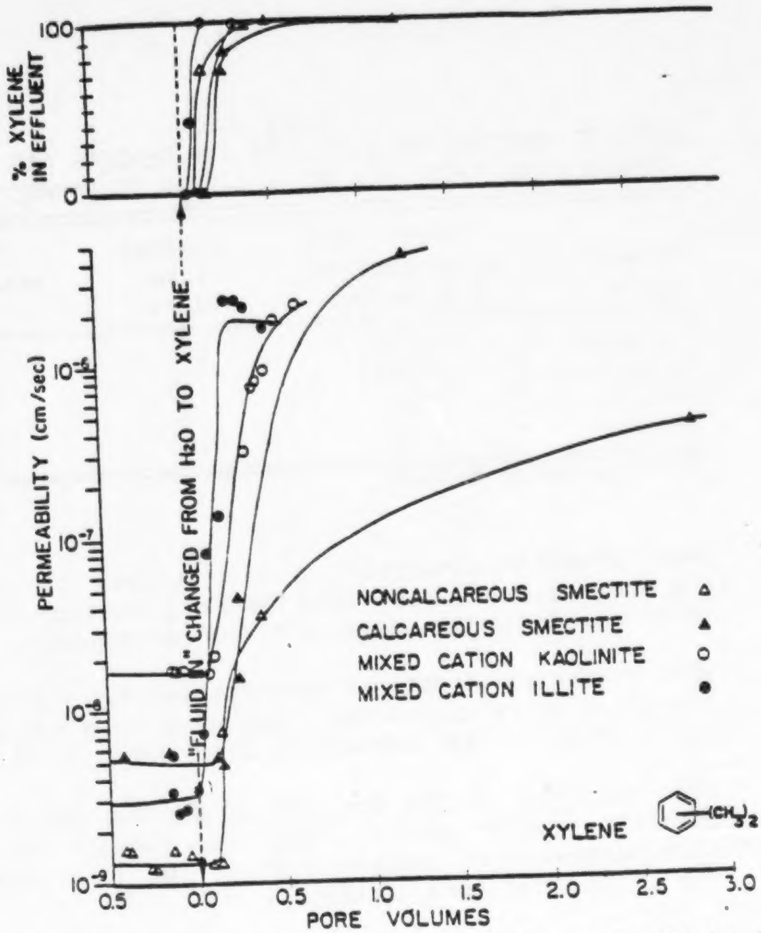

Figure 4-7. Permeability and breakthrough curves of the four clay soils treated with xylene.

Benzene -- Benzene and water were used as permeant liquids to measure the depth of penetration with time through a compacted clay subsoil (White, 1976). Approximately 90 cm long columns of the clay subsoil were compacted to 95% of standard proctor density. Test liquids were placed over the compacted soil and then air pressure was applied to the top of the liquid to simulate a hydraulic head of approximately 7 meters or a hydraulic gradient of roughly 24. Table 4-5 gives the depth of penetration with time for water and benzene when the clay liner was compacted at optimum moisture content (31% by weight) and for benzene when the clay liner was compacted at 20% and 10% water content by weight.

White (1976) presented no actual permeability values and the report lacked an adequate characterization of the clay subsoil. However, the following conclusions can be drawn from that study.

1. When compacted to optimum moisture and 95% of standard proctor density, the clay subsoil was approximately 100 times more permeable to benzene than to water.

Table 4-5
DEPTH OF PENETRATION WITH TIME FOR BENZENE AND TAP WATER PERCOLATING THROUGH A 90 cm COLUMN OF COMPACTED CLAY

Permeant liquid	Compaction water content, % by weight	Elapsed time, days	Depth of penetration, cm
Tap water	31*	100	2.4
Benzene	31*	36	90.0
Benzene	20	32	90.0
Benzene	10	0.63	90.0

*Optimum water content.

2. When properly compacted to a thickness of approximately 90 cm, the clay subsoil was found to be a suitable liner for a surface impoundment for tap water, but not for benzene.

3. When compacted at optimum moisture and 95% standard proctor density, the 90 cm thick clay liner, subjected to a hydraulic gradient of 24 would begin to leak benzene in approximately 36 days.

4. When compacted on the dry side of optimum moisture but still at 95% standard proctor density, the clay subsoil would be substantially more permeable to benzene than if the liner had been compacted at the optimum moisture content.

Heptane -- Permeabilities and breakthrough curves for four compacted clay soils permeated by heptane were measured by Anderson et al (1982) and are shown in Figure 4-8. Baseline permeability values for the clay soils were established using the standard aqueous permeant (0.01N $CaSO_4$) and are shown to the left of the dotted line in Figure 4-8.

Trends in permeability by heptane were similar to those shown by xylene; that is, the soils underwent initial permeability increases of roughly 10,000%. Following these initial large increases, the rate of increase slowed until nearly constant permeability values were observed.

Only the calcareous smectitic clay showed a significant difference in its permeability to the two neutral nonpolar liquids, with its permeability to heptane well below its permeability to xylene.

The constant permeability values eventually reached by the neutral nonpolar treated cores were probably related to the limited ability of these liquids to penetrate interlayer spaces of the clay minerals. Permeability trends for neutral nonpolar liquids differed from the continuous permeability increases observed in clay soils treated with neutral polar liquids such as acetone (Figure 4-4) and methanol (Figure 4-5).

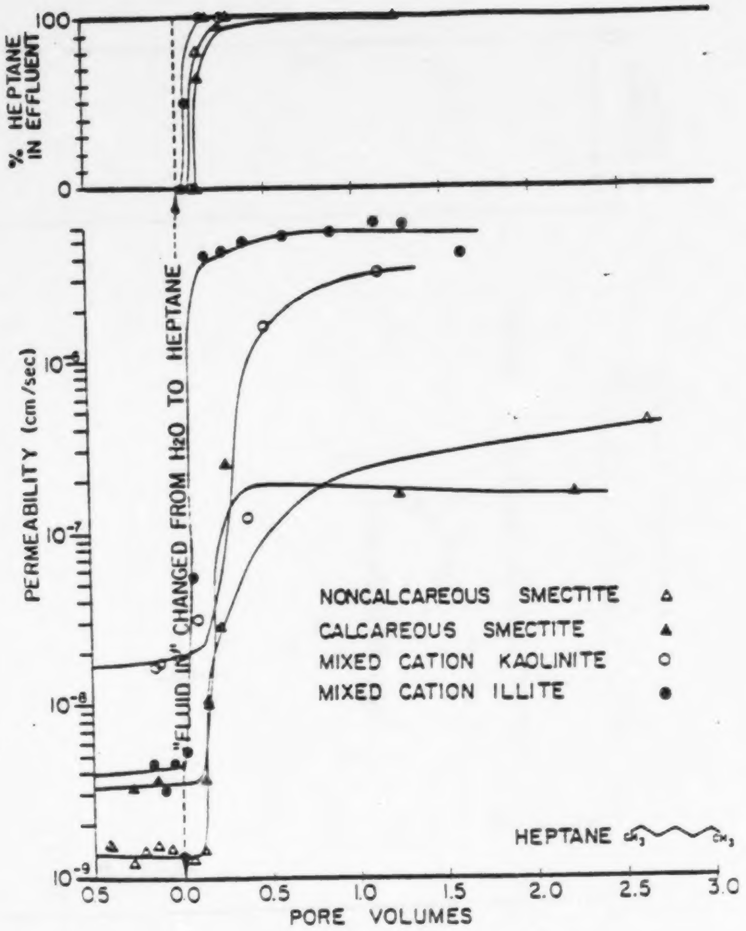

Figure 4-8. Permeability and breakthrough curves of the four clay soils treated with heptane.

Reintroduction of Water. As already indicated in this subsection, changes in the permeability of compacted clay soils permeated by organic liquids do not follow trends that would be predicted based on changes in viscosity and density of the liquid. Anderson et al (1982) studied the permeabilities of clay liners subjected to liquid sequences that might be generated in disposal facilities. They found that viscosity and density values were useless in attempting to predict the resulting liner permeabilities.

After the primary leachate (liquids present in a waste) has percolated through a clay liner, it is followed by a secondary leachate (generated by water entering the site and percolating through a waste). Anderson et al (1982) attempted to simulate this leachate sequence by following organic permeant with the standard aqueous permeant (0.01N $CaSO_4$). Figure 4-9 gives the permeability and breakthrough history of a noncalcareous smectitic clay soil sequentially permeated with standard permeant (0.01N $CaSO_4$), aniline, and then the standard permeant.

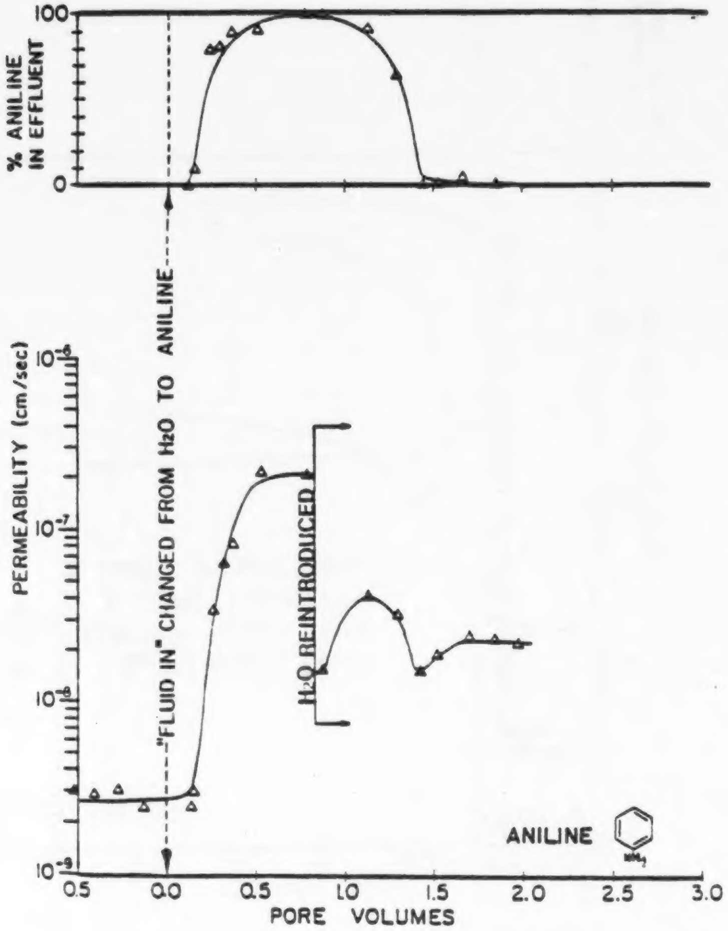

Figure 4-9. Permeability and breakthrough curve for the noncalcareous smectitic clay soil treated sequentially with standard permeant (0.01N $CaSO_4$), aniline, and standard permeant.

According to intrinsic permeability theory, more viscous aniline should render the soil less permeable than water; in fact, the opposite trend was observed. Aniline increased permeability nearly two orders of magnitude. Reintroduction of water caused a subsequent decrease in the permeability of roughly one order of magnitude. Since reintroduction of water did not return the soil to its original permeability to water, it appears that at least a partially irreversible structural rearrangement of the soil particles by the interactions of aniline with the compacted clay soil took place.

The standard aqueous permeant was also reintroduced on the noncalcareous smectitic clay soil after the soil had been permeated with methanol and ethylene glycol (Table 4-6) and the trend in permeability (observed when water was reintroduced on the aniline-treated soil) also held for both the methanol and ethylene glycol-treated soils.

TABLE 4-6. PERMEABILITY OF NONCALCAREOUS SMECTITIC CLAY SOIL TO THE FOLLOWING SEQUENCE: STANDARD PERMEANT-ORGANIC PERMEANT-STANDARD AQUEOUS PERMEANT

Organic permeant	Initial permeability to standard aqueous permeant (cm sec^{-1})	Permeability to organic permeant (cm sec^{-1})	Final permeability to standard aqueous permeant (cm sec^{-1})
Aniline	2.7 to 3.1×10^{-9}	2.2×10^{-7}	2.3×10^{-8}
Methanol	1.4 to 1.7×10^{-9}	1.1×10^{-6}	6.0×10^{-8}
Ethylene glycol	1.2 to 1.5×10^{-9}	3.1×10^{-7}	1.1×10^{-7}

4.2.4 Effect of Inorganics on Soil Permeability

Inorganic hazardous industrial wastes can have a considerable impact on the as-designed soil permeability. Some of the information available on this subject comes from studies on water quality related to irrigated soils. The relative proportion of sodium and calcium, and the total concentration of solutes have a tremendous impact on soil-fluid transmission characteristics for some particular soils (Gardner, 1945; Lunt, 1963; Quirk and Schofield, 1955).

In the next paragraphs, we summarize some of the results obtained by McNeal and Coleman (1968) who tested seven soils from western USA. The results indicated that, in general, the replacement of an originally present, high-solute concentration solution by a less concentrated one, results in a soil with a lower permeability. The reduction in permeability is proportional to the SAR value of the solution, i.e. the higher the SAR, the more drastic the drop in the K value of the soil. For solutions with SAR = , a flux corresponding to 20-40 pore volumes is sufficient to reduce the permeability to half of its original value.

Some soils were less vulnerable to this effect compared to others. Thus, the Aiken soil with 60% of the clay fraction made up of kaolinite was quite insensitive to liquid chemical composition and the drop in K value was never larger than 25% of the original value.

The Gila soil (New Mexico), on the other hand, with more than 60% clay, 48% of which is made up of montmorillonite, displayed the regular drop in permeability with a decrease in salt concentration at a low SAR and - unlike all other soils containing moderate amounts of montmorillonite - displayed a reversal of this effect upon an increase in salt concentration. The implication of this fact is that, if a liner is constructed using a soil material similar in characteristics to Gila soil, an increase in permeability is to be expected if the replacing solution (waste effluent) is more concentrated than the replaced solution. Oddly enough, this undesirable behavior is expected in a predominantly montmorillonitic clay soil, the type of material highly recommended for use as a soil liner. This observation is not intended to negate the merits of high clay content montmorillonitic soils. Indeed, the general consensus seems to be that soils with permeabilities below 10^{-8} cm sec^{-1} can be constructed using only montmorillonitic clay soils. However, the McNeal and Coleman (1966) results draw attention to the sensitivity of this type of soil and, thus, to the possibility that during service, a properly designed and constructed soil liner can increase its permeability to untolerable levels.

4.3 EFFECTS OF WASTE LIQUIDS ON FLEXIBLE POLYMERIC MEMBRANES

4.3.1 Introduction

Available information obtained from the field on the effects of waste liquids on flexible membrane liners is limited. Consequently, most of this discussion of the effects upon these liner materials of exposure to various waste liquids will be based upon laboratory and simulated exposures. The principal experience in the field with membrane liner materials has been with water impoundment and conveyance. There also has been some experience with the impoundment of brines. The experience with waste liquids, however, is relatively recent, although membrane-lined impoundments for waste water have been used since the 1960's. Some information regarding field performance with MSW leachate is reported for a few membrane liners.

Use of polymeric membrane liners for water conservation and conveyance was started in the 1940's and the first membranes were used for lining canals in 1948. These liners were butyl-coated fiberglass. Later, a number of water reservoirs, catchment basins, canals, and ponds were lined with butyl sheeting (Dedrick, 1980; Smith, 1980; Lauritzen, 1967). A variety of other polymeric membrane liners were also developed based upon such polymers as polyvinyl chloride (PVC), polyethylene (PE), chlorosulfonated polyethylene (CSPE or CSM), and chlorinated polyethylene (CPE). These were all used in the conservation, collection, storage, and conveyance of water.

Use of polymeric membrane liners for lining waste disposal sites began in the early 1970's principally because their low permeability appeared to be effective for preventing the migration of toxic constituents from waste sites. At that time, little was known as to the effects wastes would have on polymeric membranes and how long the service lives of liners might be.

Because of the potential impact that pollutants from waste disposal sites might have on the groundwater quality, EPA initiated research work in this area to determine the state-of-the-art with respect to liners and to assess the various liners available under conditions which simulated as closely as possible actual service conditions. EPA felt that the test results from this type of evaluation would give the greatest credibility to the use of lining materials for land waste disposal facilities.

Two EPA projects were undertaken to assess the effects of various wastes upon a wide spectrum of potential liner materials which have been used in the handling of water. The first project dealt with the exposure of lining materials to sanitary landfill leachate and the second with similar types of liners exposed to hazardous wastes. These liner materials included flexible polymeric membranes, soils, spray-on membranes and various admixed materials. Particular emphasis was placed on the first type because of the low permeability of these materials and their growing use. The membrane materials selected for these studies were those that were commercially available in 1973-1975 and were tested, if available, at a single thickness of 30-40 mils. In this section, the methodology used in these studies is briefly described and the available results of the exposures of the polymeric membranes are summarized. The results on other lining materials, i.e. admixes, soils, and spray-on materials, are presented in other sections of this chapter.

The first project, concerned with liners for MSW landfills, has been completed and the final report prepared (Haxo et al, 1982). The second project, concerned with liners for hazardous waste disposal facilities, is to be completed by the end of 1982.

4.3.2 Exposure of Membrane Liners to MSW Leachate

The work summarized in this section was primarily an exploratory study concerned with the interaction of liner materials with a representative MSW leachate over an extended period of time. Except for a study of seaming, the project did not discuss the design of landfills or the installation of liners, both of which are very important factors in the successful construction and functioning of disposal facilities. All membrane materials were commercial products that had been requested from the liner industry as being suitable for the lining of sanitary landfills. It was recognized at the outset of the study that the liner compositions selected and submitted by the industry had not necessarily been used in the lining of MSW landfills. However, they represented the state-of-the-art at that time and were all considered potentially effective as linings for MSW landfills.

4.3.2.1 Experimental details

To evaluate membrane liners exposed to landfill leachate, liner specimens, two feet in diameter, were placed under eight feet of ground refuse in landfill simulators (Figure 4-10). An individual simulator consisted of a two-foot diameter steel pipe, ten feet in height, placed on an epoxy-coated concrete base (Figure 4-11). The six polymeric membranes that were exposed as primary liners in the simulators were:

- Butyl rubber.
- Chlorinated polyethylene (CPE).
- Chlorosulfonated polyethylene (CSPE).
- Ethylene propylene rubber (EPDM).
- Polyvinyl chloride (PVC).

The liner specimen was sealed in the base with epoxy so that it could not be bypassed by the leachate. Each liner specimen had a seam through the center which was made either by the manufacturer or in the laboratory in accordance with the standard practice recommended by the supplier. Approximately one

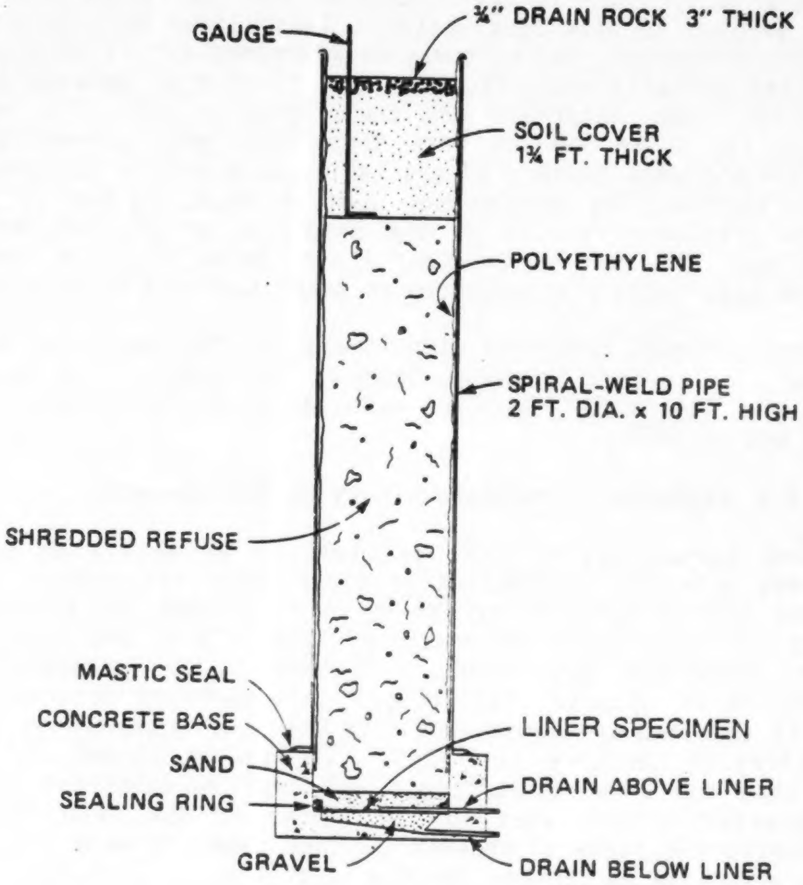
GAUGE
¾" DRAIN ROCK 3" THICK
SOIL COVER
1¾ FT. THICK
POLYETHYLENE
SPIRAL-WELD PIPE
2 FT. DIA. x 10 FT. HIGH
SHREDDED REFUSE
MASTIC SEAL
CONCRETE BASE
SAND
SEALING RING
GRAVEL
LINER SPECIMEN
DRAIN ABOVE LINER
DRAIN BELOW LINER

Figure 4-10. Landfill simulator used to evaluate liner materials exposed to sanitary landfill leachate.

cubic yard of ground refuse was compacted above each liner in approximately four-inch lifts to yield a density of 1240 pounds per cubic yard at a 30 percent water content. The refuse was covered with two feet of soil and four inches of crushed rock.

Tap water was introduced at the rate of 25 inches per year. Leachate generated in each cell was ponded above the specimen at a one-foot head by continually draining into a collection bag. Any leachate which seeped through the liner was collected below the liner.

In addition to the primary liner specimens, 2.5 x 22 inch specimens were buried in the sand above the liner and were thus totally immersed in the leachate. Two sets of each material were exposed in the simulators. One set of simulators was dismantled at the end of one year and the second set at the end of five years. Additional immersion testing was performed outside the simulators by passing leachate through cells in which 8 x 10 inch specimens of

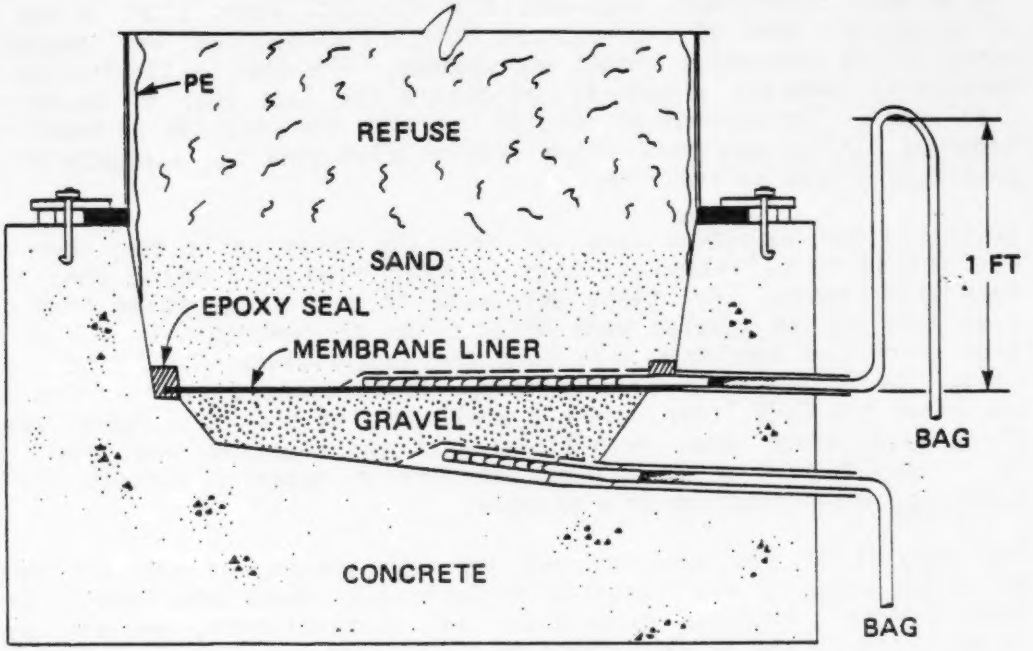

Figure 4-11. Base of the landfill simulator in which the liner materials were exposed. The refuse at the bottom of the column was anaerobic. The leachate was maintained at a head of one foot by U-tubes. Plastic bags were sealed at both outlets. Strip specimens of membrane liners were buried in the sand for exposure to leachate.

the membrane liners were hung. The specimens that were removed from the simulators and from the immersion cells were subjected to a range of physical tests normally performed on rubber and plastic materials. These tests are listed in Table 4-7.

TABLE 4-7. TESTING OF POLYMERIC MEMBRANE LINERS
Before and After Exposure to Wastes

Thickness
Tensile strength and elongation at break, ASTM D412
Hardness, ASTM D2240
Tear strength, ASTM D624, Die C
Water absorption or extraction at RT and 70°C, ASTM D570
Seam strength, in peel and in shear
Puncture resistance, Federal Test Method Standard No. 101B, Method 2065
Water vapor transmission, ASTM E96
Specific gravity and ash
Volatiles and extractables

4.3.3 Laboratory Results of Exposure to MSW Leachate

The primary liners were recovered from the simulators after 12 and 56 months of exposure. None of the membrane liners that had been well sealed into the bases of the simulators showed any seepage. The epoxy seals in 3 of the bases containing membrane liners failed during the last year of operation of the simulators. The absence of seepage confirms the very low permeability of the membrane lining materials. The results also show the adequacy of the seams that were placed in the liners.

Exposed liner specimens were cut from the bases while they were still wet and sealed in polyethylene bags to keep them in a moist condition until they were tested. All tests were made on samples as taken from the bases, i.e. none of the samples were dried prior to testing. In all of the bases from which the specimens were cut, the square-woven glass fabric and gravel below the liners were in an "as new" condition, except in the base that contained the CSPE liner, where a small area of the glass fabric was stained. Close examination under magnification of the sheeting immediately above the stain showed that a small piece of foreign material existed in the liner compound, which resulted in a pinhole.

The results of the analyses and physical testing of the specimens before and after exposure are presented in Table 4-8. These test results are divided into analyses, physical properties, and seam strength, and are arranged by liner material and by exposure time. All tests on exposed samples were made as soon as possible after removal from service. This procedure results in the determination of properties of the liners as they existed in the actual service environment.

To estimate the amount of leachate absorbed by a liner material, the volatiles content of a sample of the exposed material was measured. The absorption of leachate by a liner can be calculated when the original weight of the specimen is known such as is known when laboratory tests are made. In the field, however, it is necessary to cut a sample from the exposed liner and determine its volatiles content. In such cases, the absorption of leachate also requires information as to the extractables that are lost and the non-volatiles that are absorbed. Most leachates are essentially volatile, except for minor amounts of inorganic dissolved salts. The CSPE, CPE, and EPDM liners, in this order, had the highest volatile contents; therefore, they absorbed the greater amounts of leachate. The LDPE, PVC, and butyl liners had the lowest volatile contents and absorbed lesser amounts of leachate.

By comparing the amounts of extractable material in exposed specimens that have been dried, the amount of plasticizer or other ingredients in the compound that was lost to the leachate can be calculated. In all cases, the extractables, after 56 months, were lower than the original extractables. The magnitude of the loss, even in the case of the EPDM and PVC, was in the order of 10%.

The tensile properties of the materials varied; the tensile strength ranged approximately from 1400 to 2500 psi. The changes with exposure time were only modest and many may have been within experimental error, though several showed

TABLE 4-8. EFFECT ON PROPERTIES OF POLYMERIC MEMBRANE LINERS OF 12 AND 56 MONTHS EXPOSURE TO LEACHATE IN MSW LANDFILL SIMULATOR

Item	Test method	Exposure time, months	Butyl rubber	CPE	CSPE	EPDM	LDPE	PVC
Type of compound[a]	...	...	XL	TP	TP	XL	CX	TP
Liner number[b]	...	...	7	12	6R	16	21	17
Simulator number, 0-12 months	...	...	21	24	22	23	19	20
0-56 months	...	...	3	6	4	5	1	2
Analytical properties								
Volatiles (2 h at 105°C), %	...	0	...	0.10	0.29	0.50	0.00	0.09
	...	12	2.02	6.84	12.78	5.54	0.02	3.55
	...	56	2.37	7.61	13.90	5.74	1.95	2.08
Extractables after removal of volatiles, %	ASTM D3421, modified	0	11.0	7.5	3.8	31.8	...	37.3
		56	9.8	5.1	3.4	28.3	3.37	34.4
Solvent[c]	...	...	MEK	n-heptane	DMK	MEK	MEK	CCl_4 + CH_3OH
Physical properties								
Thickness, mils	...	0	63	32	36	51	12	21
		12	64	35	38	51	11	21
		56	64	37	37	49	10	22
Tensile strength[d], psi	ASTM D412	0	1435	2275	1765	1480	2145	2580
		12	1395	1810	1640	1455	2465	2350
		56	1465	1960	2110	1460	2585	2740
Elongation at break[d]	ASTM D412	0	400	410	250	415	505	280
		12	410	400	300	435	505	330
		56	405	385	235	375	540	340
Tensile set[d], %	ASTM D412	0	17	430	115	12	370	73
		12	14	210	105	12	430	57
		56	12	160	60	6	410	62
Stress at 200%[d], psi	ASTM D412	0	695	1330	1525	755	1260	1965
		12	685	1090	1245	740	1205	1550
		56	750	1140	1825	800	1325	1810
Tear strength (Die C)[d], ppi	ASTM D624	0	175	255	...[e]	180	390	335
		12	200	320	...	195	495	450
		56	185	170	...	130	405	285
Hardness, Durometer points, 10 second reading	ASTM D2240	0	51A	77A	79A	54A	...	76A
		12	50.5A	65.5A	64A	51.5A	...	64A
		56	51A	70A	70A	51A	...	70A
Puncture resistance[f]	FTMS 101B Method 2065							
Stress, lb		0	44.8	47.0	32.9	39.4	13.9	25.8
		12	49.5	49.8	57.0	40.1	14.8	30.1
		56	50.0	51.8	58.2	41.5	17.1	31.3
Elongation, in.		0	1.22	1.04	0.60	1.44	0.76	0.69
		12	1.20	0.98	0.88	1.18	0.80	0.70
		56	1.25	0.98	0.86	1.19	1.24	0.84

See footnotes at end of table.

TABLE 4-8 (Continued)

Item	Test method	Exposure time, months	Butyl rubber	CPE	CSPE	EPDM	LDPE	PVC
Seam strength								
Location of seam preparation	...	...	Lab	Lab	Lab	Factory	Lab	Factory
Bonding system	...	...	Adhesive (LVT)[g]	Solvent THF:Toluene 50:50	Cement	Adhesive (LVT)[g]	Heat	Cement
Peel strength, avg, ppi	...	0	3.8	10.0	>30.0[h]	5.4	15.6[h,i]	4.0
		12	2.9	5.2	3.4	2.0	...	5.1
		56	3.4	2.9	1.8	7.1	12.0[i]	5.6
Shear strength, ppi	...	0	30.0	>57.0[h]	>50.0[h]	44.5	>20.2[h]	27.2
		12	42.0	>35.0	40.2	24.3	>11.4[h,j]	>25.6[h]
		56	17.0	17.0	10.0	18.0	11	>22[h]

[a] XL = Crosslinked; TP = thermoplastic; CX = partially crystalline thermoplastic.

[b] Contractor's serial number. R indicates liner is fabric reinforced.

[c] Solvents used in extraction: DMK = acetone, MEK = methyl ethyl ketone, CCl_4+CH_3OH = 2:1 blend of carbon tetrachloride and methyl alcohol.

[d] Average of values in machine and transverse directions.

[e] Test method not applicable to fabric-reinforced materials.

[f] Rate of penetration of probe: 20 inches per minute.

[g] Low temperature curing cement.

[h] Break in specimen outside of seam.

[i] Seam failed at initial peak.

[j] Seam in the polyethylene liner used in the steel pipes; tabs in the liner specimens mounted in base were too short.

trends toward increasing values. Tests which reflect the stiffness of the materials, such as modulus, stress at 200% elongation, and hardness, showed a minimum at 12 months. These minima may reflect the changes in the composition of the leachate; at 12 months the leachate concentration showed significantly higher organic content than it did at 56 months. In all cases tear strength and puncture resistance remained at satisfactory levels over the 56 months of exposure.

Though the sheetings showed good retention of properties during exposure, there was a significant drop in several cases in the seam strength of the materials. This showed up in the CPE, CSPE, and EPDM specimens, though this loss of adhesion did not result in any seepage or leakage of the liner specimens. The fact that there was no leakage may have been due to the lack of stress on the specimens. The simulators were designed not to allow any stress on the specimens because of doubts that stress could be controlled.

Overall, the changes in the physical properties of the membranes resulting from 56 months of exposure were relatively minor. All of the membranes softened to varying degrees during the first 12 months. This change is probably due to the swelling by the leachate. In the interval of time to 56 months, the PVC, CSPE, and CPE membranes rehardened slightly, possibly indicating, in the case of the PVC membrane, loss of plasticizer and, in the case of the CSPE and CPE membranes, crosslinking of the polymers. They all recovered most of their tensile properties that were lost due to the initial softening. These materials were all thermoplastic and unvulcanized.

Of the six polymeric membranes, the LDPE film best maintained original properties during the exposure period as shown in Table 4-8; it also absorbed the least amount of leachate. However, this membrane, which was 10 mils in thickness, probably has too low a puncture resistance for use in lining a landfill. This deficiency was confirmed in handling it in the lining of the steel pipes of the simulators, in the preparation of the primary liner specimens, and in the making and use of the LDPE leachate collection bags. The butyl and EPDM liners changed slightly more in physical properties than did the LDPE liner during the exposure period.

The fact that, except in the bases in which the epoxy resin sealing ring deteriorated, no leachate appeared below the membrane liners during the exposure period indicates that the very low permeability of the polymeric membranes is maintained after extended exposure to MSW leachate.

A comparison of the swelling of membrane materials in water and in leachate is presented in Table 4-9. The composition of the leachate at the end of the first year of operation of the simulator is presented in Table 4-10. The data for most of the membrane liners show that the swelling in leachate is significantly higher than that in water in spite of the dissolved inorganic constituents in the leachate. This greater swelling is probably due to the organic constituents in the leachate. The neoprene and CPE membranes swelled less in leachate than in water.

TABLE 4-9. WATER AND LEACHATE ABSORPTION BY POLYMERIC LINERS[a]
(Data in percent absorbed by weight)

	Liner no.	Water-RT 1 year	Leachate 1 year
Butyl rubber	7[b]	1.60	1.78
	22	1.70	2.32
	24	1.10	1.0
Chlorinated polyethylene (CPE)	12[b]	13.10	9.0
	13[c]	19.60	12.4
	23	15.50	10.3
Chlorosulfonated polyethylene	3	17.40	20.0
	4[c]	18.00	19.0
	6[b, c]	9.20	13.64
	14[c]	11.20	8.71
Ethylene propylene rubber (EPDM)	8	1.40	5.95
	16[b]	4.80	5.50
	18	...	...
	25	1.50	5.99
	26	1.60	8.99
Neoprene	9	22.7	8.73
Polybutylene	20	0.25	0.33
Polyethylene	21[b]	0.20	0.25
Polypropylene	27	0.28	0.40
Polyvinyl chloride	10	1.85	6.72
	11	1.85	5.0
	15	2.10	4.64
	17[b]	1.85	3.29
	19	0.60	0.75

[a] Haxo (1977).

[b] Liners mounted in generator bases.

[c] Fabric-supported liner.

TABLE 4-10. ANALYSIS OF LEACHATE[a]

Test	Value
Total solids, %	3.31
Volatile solids, %	1.95
Nonvolatile solids, %	1.36
Chemical oxygen demand (COD), g/L	45.9
pH	5.05
Total volatile acids (TVA), g/L	24.33
Organic acids, g/L	
Acetic	11.25
Propionic	2.87
Isobutyric	0.81
Butyric	6.93

Source: Haxo, et al (1979).

[a] At the end of the first year of operation when the first set of liner specimens were recovered.

In Table 4-11 the absorption of the primary and buried liner specimens after twelve months of exposure to leachate is compared with samples of similar materials immersed in leachate for 8 and 19 months. The data show that the buried specimens which are exposed on both sides to the leachate tend to swell slightly more than the primary specimens which are exposed to the leachate on only one side. The swelling of the specimens, that were immersed completely in leachate which flowed by the specimens as they were hung in the immersion cells, was equal to or greater than the swell of the buried specimens. Leachate flowed by the latter specimens but at a slower rate.

Overall, these results indicate that the leachate tends to swell the membranes more than does water and that exposure from two sides yields somewhat higher swelling values. In some cases, there was a levelling off with time of the degree of swelling by the leachate. However, the composition of the leachate was simultaneously changing, with the levels of the organic constituents dropping with time.

Significant variations in properties and effects of the exposure can be observed among the membranes of a given generic type, as shown in Figures 4-12 and 4-13 regarding absorption of leachate and tensile strength retention, respectively. In Figure 4-12 the specific membranes are numbered on the bars.

TABLE 4-11. SWELLING[a] OF POLYMERIC MEMBRANES ON EXPOSURE TO MSW LEACHATE

	Exposed in simulators, months				Immersion in flowing leachate, months		
	Primary		Buried				
	12	56	12	56	8	19	30.5
Butyl rubber	2.0	2.4	1.8	2.0	1.4	2.6	1.96
Chlorinated polyethylene	6.8	7.61	9.0	10.1	7.9	14.4	9.95
Chlorosulfonated polyethylene	... 12.8	... 13.90	20.0 13.6	14.7 17.0	18.6 12.1	22.8 14.9	17.24 14.53
Ethylene propylene rubber	5.54	5.74	6.0	6.5	2.9	3.8	5.98
Polybutylene	...	...	0.3	0.2	-0.2	0.7	0.46
Polyethylene	0.02	1.95	0.3	...	0	0.2	0.10
Polyvinyl chloride	... 3.6 ...	... 2.08 ...	5.0 3.3 0.8	2.0 1.30[b] 0.5	2.4 2.3 0.9	4.4 4.4 1.9	3.87 3.02 1.45

[a] Measured by percent volatiles of the exposed material.

[b] Forty-three months in simulator.

The length of the bars show the range of absorption values obtained for a liner material of a given polymer type. For example, one neoprene liner at 8 months swelled approximately 2% and another approximately 20%; at 19 months the spread had become 3% and 32%, respectively. The effects of 8, 19, and 31 months of immersion in leachate upon the S-200 modulus of the membranes are shown in Table 4-12 and upon tensile strength are shown in Figure 4-14.

Table 4-13 presents the variations observed with different PVC membrane specimens that had been buried in the sand above the liners in the simulators.

4.3.4 Field Verification of Membrane Liner Performance

Though considerable information has been and is being developed in laboratory and pilot studies, information regarding the performance of lining materials in extended service in MSW landfills with exposure to leachate has been very limited. First, the lining of landfills, particularly with flexible polymeric membranes, is relatively new, i.e. from the early 1970's. Second, effective and economic methods have not been developed for sampling and repairing the holes cut in the linings of landfills.

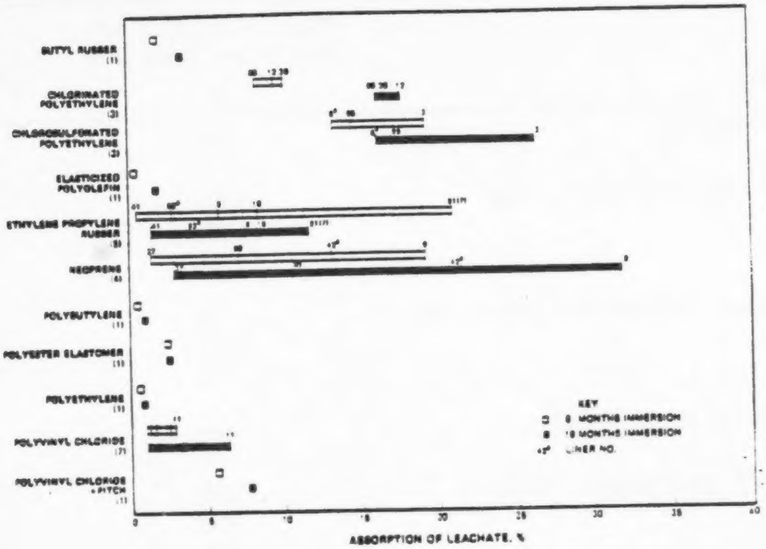

Figure 4-12 Ranges of swelling values of membranes of different polymeric types during immersion in leachate for 8 and 19 months. The number of different liners of a given polymer that are included in the test is shown in parentheses.

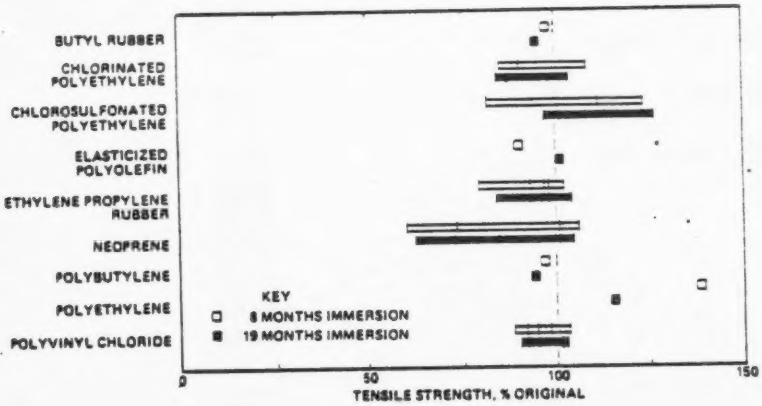

Figure 4-13 Ranges of retentions of tensile strength of membranes of different polymeric types on immersion in landfill leachate for 8 and 19 months. Tensile strength data were obtained by averaging the tests in machine and transverse directions.

TABLE 4-12. RETENTION OF MODULUS[a] OF POLYMERIC MEMBRANE LINER MATERIALS ON IMMERSION IN LANDFILL LEACHATE

Polymer	Modulus S-200 of unexposed membrane, psi	Retention on exposure of original value, % 8 mo.	19 mo.	31 mo.
Butyl rubber	685	86	90	98
Chlorinated polyethylene	1330	85	89	95
	1205	89	90	104
	810	98	106	133
Chlorosulfonated polyethylene	35	54	46	57
	1525[b]	116[b]	136[b]	...
	1770	77	108	130
Elasticized polyolefin	1020	99	103	107
Ethylene propylene rubber	655	134	131	134
	755	111	109	117
	1040	100	99	105
	920[b]	98[b]	98[b]	104[b]
	855	91	92	98
Neoprene	1235	79	77	76
	1635	100	100	99
	1340	93	101	115
Polybutylene	3120	101	101	106
Polyester elastomer	2735	102	98	100
Polyethylene	1260	106	102	106
Polyvinyl chloride	2125	87	85	98
	1965	80	84	94
	1740	89	94	112
	1720	91	91	104
	1705	92	105	117
	2400	79	88	101
	2455	96	95	105
Polyvinyl chloride + pitch[c]	1020	85	86	...

[a] Average of stress at 200% elongation (S-200) measured in machine and transverse directions.

[b] Membrane is fabric reinforced.

[c] S-100 values given; original and subsequent exposed specimens failed at less than 200% elongation.

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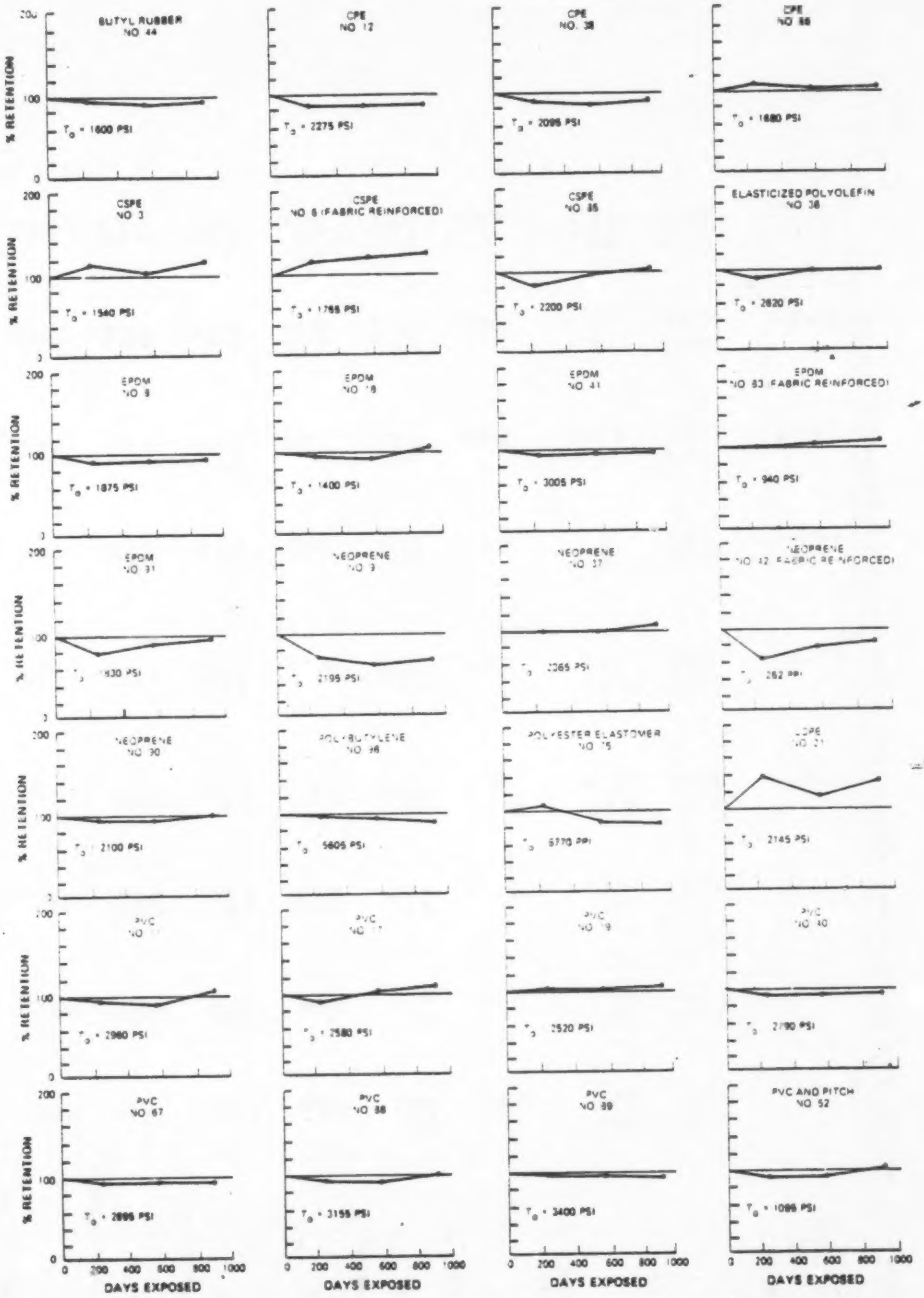

Figure 4-14 Retention of tensile strength of the individual polymeric membranes as a function of immersion time in landfill leachate. Tensile strength values based upon the average data obtained in the machine and transverse directions. Liner numbers and initial tensile strength for each liner are shown. Data are given for 8, 19, and 31 months.

TABLE 4-13. PROPERTIES OF PVC MEMBRANE SPECIMENS BEFORE AND AFTER EXPOSURE TO LEACHATE IN MSW LANDFILL SIMULATORS

Specimen number[a]	10	11	15	17	19	67	88	92A	93
Simulator number	1	1	11	11	1	11	12	12	11
Nominal thickness, mils	34	31	11	20	21	21	20	22	11
Exposure time, months	56	56	43	43	56	13	13	13	13
Analytical properties:									
Volatiles, %									
Initial	0.30	0.11	0.47	0.08	0.05	0.03	0.17	0.23	0.12
Final	6.32	1.97	1.92	2.10	0.51	0.66	0.67	1.29	1.73
Change	+6.02	+1.86	+1.45	+2.02	+0.46	+0.63	+0.50	+1.06	+1.61
Extractables, %									
Initial	32.54	33.90	...	37.25	38.91	...	33.46	...	32.26
Final	30.53	31.37	33.33	34.39	36.13	36.25	30.64	30.72	29.34
Change	-2.01	-2.53	...	-2.86	-2.78	...	-2.82	...	-2.92
Physical properties:									
Thickness, mils									
Initial	32	30	10	20.5	22	22	20	20	11
Final	34	31	11	20	24	21	20	21	11
Change	+2	+1	+1	-0.5	+2	-1	0	+1	0
Tensile at break[b], psi									
Initial	3400	3140	2360	2640	2780	3020	3395	2435	3035
Final	3140	2955	2180	2760	2765	2995	3590	2655	3145
Retention, %	92	94	92	105	100	99	106	109	104
Elongation at break[b], %									
Initial	280	325	200	270	330	385	325	245	350
Final	330	315	280	380	340	345	310	335	315
Retention, %	118	97	140	141	103	90	95	137	90
S-200[b], psi									
Initial	2610	2295	2360	2080	1890	1820	2610	2170	2055
Final	2420	2355	2000	1800	2020	2150	2730	1895	2410
Retention, %	93	103	90	87	107	118	105	87	117
Tear resistance[b] (Die C)									
Initial	390	380	295	352	295	340	460	435	362
Final	450	425	380	385	345	360	560	420	390
Retention, %	115	112	129	109	117	106	122	96	108
Hardness, Duro A, 10 sec. rdg.									
Initial	82	80	72	76	72	75	80	82	78
Final	85	85	69	72	75	73	78	75	75
Change	+3	+5	-3	-4	+3	-2	-2	-7	-3
Puncture strength (20 ipm)									
Stress, lb									
Initial	42.9	39.5	12.8	25.8	24.0	27.8	28.6	27.4	15.9
Final	61.2	59.7	15.4	29.6	35.9	35.1	34.0	33.4	18.9
Retention, %	143	151	120	115	150	123	119	122	119
Elongation, in.									
Initial	0.62	0.62	0.61	0.69	0.71	0.68	0.56	0.62	0.55
Final	0.78	0.80	0.70	0.88	0.80	0.78	0.68	0.74	0.56
Retention, %	126	129	115	128	1.13	115	121	119	102

[a] Contractor's identification number.

[b] Tensile and tear properties in machine direction only except for No. 93 which is reported in transverse direction only.

Several lined disposal sites which were being closed became available for sampling of the liners that had been used. These sites were either small cells made in demonstration projects or full-scale sites that were being closed because of their inadequate size. These sites were:

- A demonstration MSW cell in Crawford County, Ohio, which had been in service for six years.
- A sludge lagoon in the northeastern United States.
- The Boone County, Kentucky, field site of the EPA, which had been operating for more than nine years.
- Two experimental cells which had been in operation for four years at Georgia Institute of Technology.

Samples of the liners were taken from each of these sites and submitted to laboratory tests to assess the physical properties and compositions of the exposed samples. However, no unexposed samples were retained for reference purposes to determine the retention in properties. Observations on the liners from each of the sites are discussed below.

4.3.4.1 PVC liner in small demonstration landfill

The Crawford County, Ohio demonstration landfill was placed in the spring of 1971 and lined with a 30 mil PVC sheeting. It had been designed to compare conventionally-processed solid waste with a shredded waste, and with a rough compacted waste. The three types of refuse were placed in cells lined with the PVC membranes that were essentially large waterproof bags.

The effect of water content on consolidation and decomposition of the refuse was to be determined but the cells were flooded with water in a heavy rainfall just before the cells were to be sealed. As a consequence, the refuse in all cells was flooded and probably remained so from 1971 until they were opened in May 1977. A layer of clay had been placed on the PVC liner and when the cells were opened and the clay tested, it was found to have a low permeability. Thus, it appears that none of the leachate in the cell had contacted the liner.

The testing results of both the liner that was at the top of the cell under two feet of clay and the liner that was at the bottom of the cell are reported in Table 4-14. The liner beneath the refuse had swollen somewhat and softened. There was also an indication that the liner at the top had lost some plasticizer. The sheeting itself had sustained considerable distortion during its exposure due to rough ground or to the gravel on which it was placed. In spite of the lack of a retained sample for comparison, it appears, judging by the test values of the exposed sheeting, that the overall properties, including the seam strength, probably changed little during the exposure.

TABLE 4-14. PROPERTIES OF 30 MIL POLYVINYL CHLORIDE LINER RECOVERED FROM A DEMONSTRATION LANDFILL IN CRAWFORD COUNTY, OHIO

Liner number Exposure	96 Top of fill	97A Bottom of fill
Analytical properties:		
Volatiles, (2 h at 105°C), %	0.41	1.33
Specific gravity (dry basis)	1.260	1.265
Ash (dry basis), ASTM D297, %	6.14	6.01
Extractables, (dry basis) ASTM D3421, %	34.10	34.43
Physical properties:		
Thickness, mil	30	28
Tensile strength, psi	2630	2515
Elongation at break, %	350	340
S-100, psi	1270	1135
S-200, psi	1790	1695
Tear strength, ppi	372	342
Hardness, Durometer points	70A	72A
Puncture resistance, lb	41.4	37.3
Elongation, in	0.66	0.65
Seam strength in shear, ppi	49.5	45.5
Locus of failure[a] -	SE	SE-BK

[a] SE = Break at seam; BRK = break in tab.

4.3.4.2 PVC liner in sludge lagoon

A disposal facility containing a brewery sludge and lined with a 15 mil PVC sheeting was being closed after having been in operation for 6.5 years. Both weathered and buried samples were obtained from the site. Testing indicated a broad range of effects upon the PVC liner, i.e. from complete deterioration, where the liner had been exposed to the weather, to almost no apparent deterioration where the liner had been under either soil or sludge. No retained sample was available, however, to use as a control for assessing changes. Also, it is not certain whether any of the sheeting had been exposed to anaerobic conditions.

The samples taken from the under the soil or sludge ranged in volatiles content from approximately 1% to more than 8%. They also ranged in extractables from 29 to 36.7%, indicating that PVC sheeting, even under a cover, can lose plasticizer.

The sheeting that had been exposed to the weather was taken from the berm and had become so brittle that it fragmented on touch. Analytical and physical test data of samples of three of the recovered sheetings are presented in Table 4-15. It is quite apparent from these data that a PVC liner must be covered and probably should be thicker than 15 mils.

4.3.4.3 Boone County field site

The closure (Emcon, 1981) of the Boone County Field Site provided an opportunity to recover CSPE, CPE, and LDPE lining materials that had been under exposure to conditions of an MSW landfill environment for more than nine years. This site had been operated by the Solid and Hazardous Waste Research Division of the EPA from 1971 through 1980 (Wigh and Brunner, 1981).

Four samples of sheetings, three chlorosulfonated polyethylene (CSPE) and one low-density polyethylene (LDPE) were taken from Test Cell 1 and six samples of the chlorinated polyethylene (CPE) liner were taken from Test Cell 2-D; four of the latter were taken from the bottom of the cell and two that had been exposed to weather from above ground. All three liner materials were unsupported, and all samples, except the two that were above ground, were exposed to leachate. No retained samples of the original materials were available, nor were any test data available on the specific lots of sheetings used in these cells. The data on representative samples are presented in Table 4-16, which includes data on LDPE, CSPE, CPE taken from the bottom of the cell and CPE taken from above the ground. Test results on all of the CSPE samples were very similar and are averaged in the table.

During the operation of the cell, an attenuated leachate contacted the CSPE sheeting. The quantity that permeated through the soil and was collected was a fraction of one percent of the amount generated in the cell. The quality of this leachate was more dilute than the leachate that was collected above the clay. In other words, these CSPE samples were in contact with a dilute leachate for approximately nine years.

The CSPE liner samples showed a substantial absorption of the dilute leachate, ranging in swelling from 23.9 to 28.4%. For the sample that had a 28.4% volatiles content, this is equivalent to a 39% increase in weight or an increase of 57% in volume based upon the original composition.

The LDPE film was clear after the surface stain was removed by washing. and appeared to be unaffected by the exposure to the MSW leachate during the nine years of exposure. The sample which was in direct contact with the full-strength leachate showed little swelling and its properties appeared to be normal for a LDPE of 6-7 mils thickness.

TABLE 4-15. PROPERTIES OF 15 MIL POLYVINYL CHLORIDE LINER MEMBRANE EXPOSED AT A SLUDGE LAGOON IN THE NORTHEAST FOR 6.5 YEARS

	Covered by soil or sludge		Exposed to weather	
Analytical properties:				
Volatiles, %	8.15	3.13	8.46	3.41
Ash (db), %	4.35	3.97	5.83	...
Specific gravity (db)	1.31	1.25	1.32	...
Extractables (db)[a], %	29.0	36.7	25.8	24.8
Physical properties[b]:				
Thickness, mil	15	16	16	11.6
Tensile at break, ppi	43.0	45.5	38.6	32.1
Elongation at break, %	225	375	175	7
S-100, ppi	34.7	21.0	35.5	...
S-200, ppi	41.9	29.3	...	...
Tear strength, Die C, lb	6.7	5.0	6.8	...
Hardness, durometer points	86A	75A	81A	...

[a] Extractions performed with a 2:1 blend of carbon tetrachloride and methyl alcohol.

[b] Tensile and tear values are averages of machine and transverse directions.

The samples of CPE lining material taken from the bottom of the cell had been in direct contact with the leachate generated in Cell 2-D and were stiff and leathery. They showed a significant absorption of the leachate, ranging in volatiles content from 16.7 to 18.8%.

The volatiles content of 18.8% is equivalent to an increase of 23% in weight based upon the original, or an increase of 31.7% on the volume basis. The data on the volatiles and the data on the devolatilized samples indicate that two different compositions were involved. The A and C samples are one composition and the B sample another composition. The two B samples have somewhat less ash content, lower volatiles, and lower extractables. Differences also occur in the results of the physical property tests.

TABLE 4-16. EFFECTS ON CHLOROSULFONATED POLYETHYLENE, LOW-DENSITY POLYETHYLENE AND CHLORINATED POLYETHYLENE SHEETINGS OF EXPOSURE IN MSW CELLS AT BOONE COUNTY FIELD SITE FOR 9 YEARS

	In Cell 1		In Cell 2-D	
Property	CSPE[a,b] Below clay layer	LDPE[c] In contact with cement	CPE[a] Under waste	CPE[a] Above ground
Analytical properties:				
Volatiles[d], %	26.5	...	18.8	6.63
Ash (db)[e], %	22.4	0.15	13.36	13.21
Specific gravity (db)	1.446	...	1.372	1.34
Extractables (db), %	3.27	1.10	4.81	4.42
Physical properties:				
Thickness, as received, mil	43.8	7.0	41.5	34.0
Thickness, after drying, mil	45.7[f]	6.6[f]	39.2	...
Tensile at yield, ppi	...	9.9	...	...
Breaking factor, ppi	52.6	10.6	49.8	64.3
Elongation at break, %	325	285	280	305
S-100, ppi	19.2	9.6	26.9	37.2
S-200, ppi	32.4	9.65	39.8	49.1
Tear strength, lb	6.5	2.9	7.3	7.2
Hardness, Durometer points	57A	...	67A	71A
Puncture strength				
Stress, lb	34.2	7.0	36.6	46.4
Elongation, in.	0.89	0.37	0.78	0.68

[a] Nominal thickness of sheeting = 30 mils.

[b] Averages of the results on three samples of the CSPE liner; all three were taken from below the clay layer and had been in contact with full-strength leachate.

[c] Nominal thickness of sheeting = 6 mils.

[d] Volatiles equals the accumulated weight loss on drying for seven days in air at room temperature, six days in oven at 50°C, and two hours in air oven at 105°C.

[e] Dry basis.

[f] Specimens shrank and became thicker.

In spite of the significant swell of the CPE sample that had been exposed to the full-strength leachate, the properties of the swollen CPE were reasonably good.

Compared with the samples that had been exposed to the leachate in the cell, the weathered materials are significantly higher in tensile strength, moduli, and puncture resistance (Table 4-16). The lower values for the leachate-exposed CPE probably reflect the swelling by leachate; however, crosslinking during exposure may contribute to the higher values of the weathered samples.

4.3.4.4 CSPE membrane liner without fabric reinforcement

The pilot scale landfill cells at Georgia Institute of Technology were constructed and put into operation as part of a research investigation to study the effect of leachate recycling upon the consolidation and stabilization of municipal solid waste. The cells consisted of two adjoining structures, each with a 10 x 10 ft base and 17 ft in height. They were built of concrete and fully lined with an unsupported CSPE membrane. One cell was left open at the top and the other sealed. Two drain systems were incorporated in the bottom of each cell, one in the gravel layer above the liner and one in the gravel layer between the liner and the concrete base. Shredded MSW was added to the cells and compacted to a density of 540 lb yd^{-3}. The open cell had 9 ft of waste and the closed cell 8.5 ft of compacted waste. In both cases another layer of gravel with the leachate distribution system was above the compacted waste. Two feet of soil were then added to cover the cell. The amount of rainfall reaching the open cell was monitored and an equivalent amount of water was added to the closed cell.

At the conclusion of the study after four years of operation, the cells were emptied and the liners recovered. Because the liners in the two cells were exposed to a variety of conditions within the cells, the effects of this variation in location of a liner within a site on liner performance could be measured. The liner in the cell that was open at the top encountered normal weather conditions and sunlight, as well as differences in exposures between the waste and the soil cover. The liner in the sealed cell encountered the moist air in the cell above the soil, the soil, and the refuse.

The data on the different exposures are presented in Table 4-17. In particular, they show the greater absorption of leachate and moisture by liners in the soil and in the waste. They also show the difference between the liner that was on the north wall facing the south and the sheeting on the south wall facing north. The sheeting on the north wall yielded the maximum increase in modulus and in cure. The sheeting that was below the waste appeared to lose in ash, perhaps due to solubilization by the leachate.

4.3.5 Exposure of Membrane Liners to Hazardous Wastes

The second study was concerned with the laboratory evaluation of a wide range of liner materials, including membranes, on exposure to a variety of hazardous wastes. Our basic approach was to expose specimens of the various commercial lining materials under conditions which simulated real

TABLE 4-17. EXPOSURE OF CSPE LINER WITHOUT FABRIC REINFORCEMENT IN PILOT-SCALE MSW LANDFILL CELLS AT GEORGIA INSTITUTE OF TECHNOLOGY[a]

Cell	Open Cell				Closed cell		
Compass orientation	N	SE	N	SW	SW	N	E
Level in cell	Above soil	Above soil	In soil	Below waste	Above soil	In soil	Below waste
Thickness, mil	29.1	29.1	31.9	52.8	33.1	34.3	39.0
Analytical properties:							
Volatiles, %	3.62	9.01	13.8	23.7	2.3	19.0	26.5
Extractables (db), %	...	1.50	...	...	2.00	...	...
Ash (db), %	41.9	39.9	40.3	36.6	40.6	40.7	37.8
Physical properties[b]:							
Tensile at break, psi	2380	2190	1740	1335	1770	1450	1450
Elongation at break, %	360	350	545	485	570	545	485
Set after break, %	95	72	227	170	206	206	154
S-100, psi	655	610	405	320	420	280	335
S-200, psi	930	740	510	420	510	375	450
Tear resistance, ppi	200	140	187	151	213	159	138
Puncture resistance:							
Thickness, mil	30.7	22.0	34.5	40.3	32.7	36.4	41.2
Stress, lb	36.8	27.9	33.4	41.6	27.3	33.9	39.0
Elongation, in	0.88	0.51	1.33	1.61	1.12	1.72	1.71
Hardness, Durometer points	76A	78A	64A	56A	75A	60A	51A
Seam strength:							
Shear, ppi	33.4	...	35.5	30.0	40.5	34.3	22.2
Peel, average, ppi	17.4	...	14.2	12.4	14.2	15.8	13.8

[a] Pohland et al (1979).

[b] Tensile and tear values are averages of machine and transverse directions.

[c] Value reported is the maximum stress. Seam failed after initial maximum.

service, using actual wastes, to measure seepage through the specimens, and to measure effects of exposure by following changes in important physical properties of the respective lining materials.

In this study, various membrane lining materials were subjected to seven types of exposure testing:

- Bench screening tests; small specimens immersed in wastes.
- Primary exposure cells; one-side exposure to waste.
- Weather test; roof exposure.

- Weather test; small tubs lined with membranes and containing wastes.
- Water absorption at room temperature and 70°C.
- Membrane bags containing wastes in deionized water; one-side exposure.

The above exposure conditions are discussed and tests presented:

1. Primary exposure tests.
2. Immersion tests of membranes.
3. Pouch test of membranes.

4.3.5.1 Exposure of primary liner specimens

In this part of the study, specimens of one square foot of eight different polymeric membrane liners were exposed below one foot of waste in cells which simulated ponds. The wastes included two strong acid wastes, a strong alkali waste, an oil refinery tank bottom waste, a lead waste from gasoline, saturated and unsaturated hydrocarbon wastes, and a pesticide waste. Characteristics of these wastes are presented in Tables 4-18 and 4-19.

The exposure cell for the primary specimens is shown schematically in Figure 4-15. A similar type of exposure cell has been used for the thick admix and soil liners (Figure 4-16). Each membrane specimen was prepared with a field-type seam across the center made according to the recommended practice of the supplier of the membrane. Two specimens of each liner material were placed in two sets of cells which were loaded with portions of the same waste. The cells were dismantled at two exposure times and the liner specimens were recovered, analyzed, and their physical properties measured.

The first set of primary specimens was removed after one year of exposure and the second set after approximately 3.5 years of exposure to the wastes. Selected data on the second set after 3.5 years of exposure are presented in Tables 4-20 and 4-21. Table 4-20 presents the results of tests for volatiles and extractables of the eight membrane liners exposed in four different wastes. The volatiles were determined on a sample of the liner immediately after removal from the waste and the extractables were determined on the specimen which had been devolatilized. Results show the variation in the volatiles and extractables both with respect to the polymer type and the waste. There are indications that, in some cases, the plasticizer which was in the original compound was removed during the exposure period. In other cases, the extractables were higher, indicating the absorption of nonvolatile constituents in the waste.

Table 4-21 presents the effects of one and three years of exposure upon ultimate elongation and S-100 modulus of the same liner materials in the same wastes.

The effects of 3.5 years of exposure to the wastes varies considerably with the liner material and the waste. Only one material, a polyester elastomer,

TABLE 4-18. WASTES IN EXPOSURE TESTS
Phases

Type of waste	Name	Organic Phase I	Water Phase II	Solids Phase III
Acidic	"HFL"[a]	0	100	0
	"HNO_3, HF, HOAC"[b]	0	100	0
Alkaline	"Slopwater[a]	0	100	0
	"Spent caustic[b]	0	95.1	4.9
Lead	"Low lead gas washing"))Blend[b]	10.4	86.2	3.4
	"Gasoline washwater")	1.5	98.1	-
Oily	"Aromatic oil"[b]	100	0	0
	"Oil Pond 104"[b]	89.0	0	11.0
	"Weed oil[a]	20.6	78.4	11.0
Pesticide	"Weed killer"[b]	0	99.5	0.5

[a] In immersion tests only.

[b] In both primary exposure and immersion tests.

TABLE 4-19. WASTES IN EXPOSURE TESTS
pH, Solids, and Lead

Type of waste	Name	pH Water phase	Solids, %		Lead, ppm
			Total	Volatile	
Acidic	"HFL"	4.8	2.48	0.9	-
	"HNO_3, HF, HOAC"	1.5	0.77	0.12	-
Alkaline	"Slopwater"	12.0	22.43	5.09	-
	"Spent caustic"	11.3	22.07	1.61	-
Lead	"Low lead gas washing"	7.2	1.52	0.53	34
	"Gasoline washwater"	7.9	0.32	0.17	11
Oil	"Aromatic oil"	-	-	-	-
	"Oil Pond 104"	-	*ca.* 36	*ca.* 31	-
	"Weed oil"	7.5	1.81	1.00	-
Pesticide	"Weed killer"	2.7	0.78	0.46	-

Source: Haxo, 1980a.

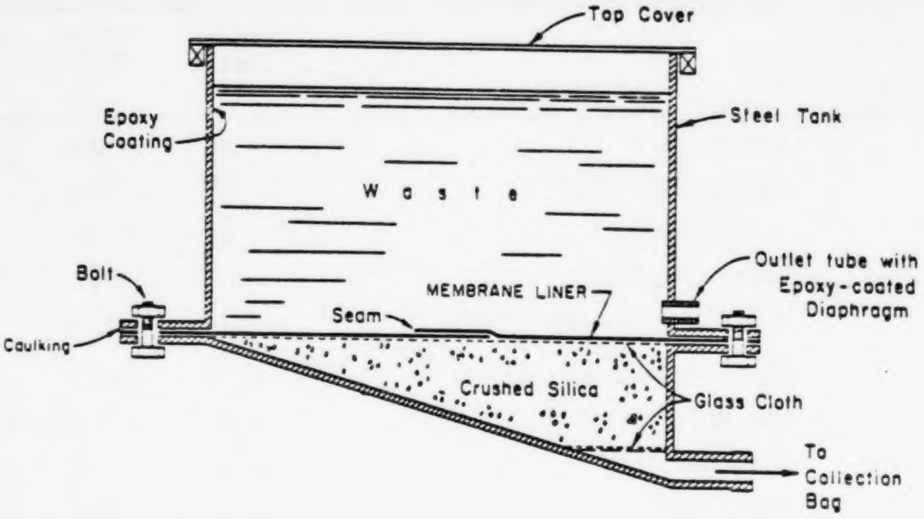
Top Cover
Epoxy Coating
Steel Tank
Waste
Bolt
Outlet tube with Epoxy-coated Diaphragm
MEMBRANE LINER
Seam
Caulking
Crushed Silica
Glass Cloth
To Collection Bag

Figure 4-15. Exposure cells for membrane liners. Dimensions of the steel tank are 10 x 15 x 13 inches in width, length, and height.

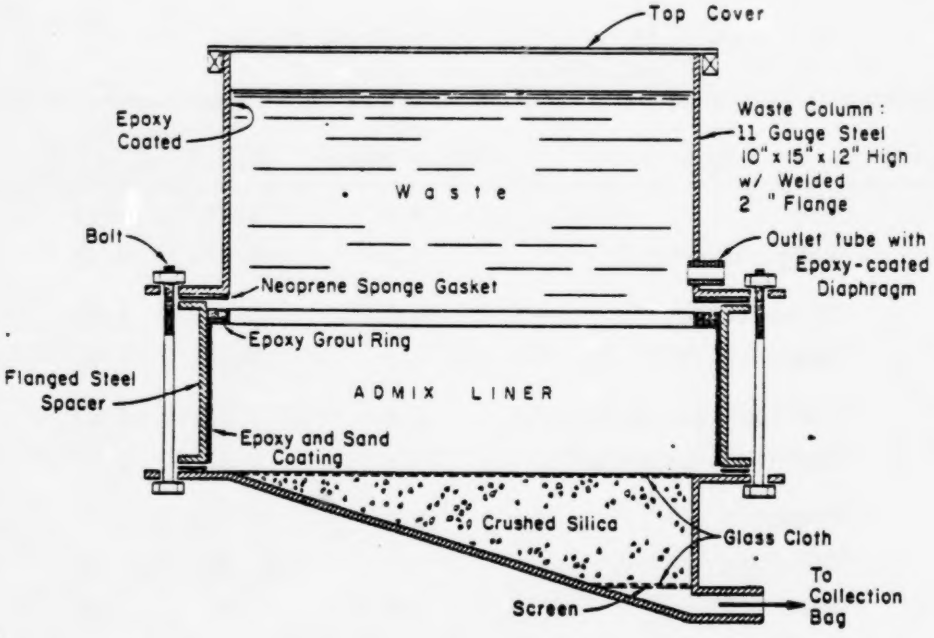
Top Cover
Epoxy Coated
Waste Column: 11 Gauge Steel 10" x 15" x 12" High w/ Welded 2 " Flange
Waste
Bolt
Outlet tube with Epoxy-coated Diaphragm
Neoprene Sponge Gasket
Epoxy Grout Ring
Flanged Steel Spacer
ADMIX LINER
Epoxy and Sand Coating
Crushed Silica
Glass Cloth
To Collection Bag
Screen

Figure 4-16. Exposure cell for thick liners.

TABLE 4-20. VOLATILES[a] AND EXTRACTABLES[b] OF PRIMARY POLYMERIC MEMBRANE LINER SPECIMENS AFTER EXPOSURE TO SELECTED WASTES

Liner data		Compound data		Volatiles, %					Extractables, %			
					Waste and exposure time in days (d)				Waste and exposure time in days (d)			
					Pesticide	HNO3	Caustic	Lead	Pesticide	HNO3	Caustic	Lead
Polymer	No.[c]	Type[d]	Extractables, %	Unexposed	1260 d	1220 d	1250 d	1340 d	1260 d	1220 d	1250 d	1340 d
Butyl	57R	VZ	6.4	0.29	4.8	11.5	1.4	3.5	7.6	8.7	7.9	7.9
CPE	77	TP	9.1	0.00	7.9	13.2	2.8	19.2	9.4	10.6	9.1	7.2
CSPE	6R	TP	3.8	0.29	9.7	7.2	5.8	11.4	5.4	4.6	3.8	6.0
ELPO[e]	36	TP	5.5	0.15	...[f]	5.3	...[f]	1.5	...[f]	7.1	...[f]	8.1
EPDM	26	VZ	18.2	0.50	6.3	12.0[g]	1.3	5.3	25.2	22.8	24.0	26.0
Neoprene	43	VZ	13.9	0.45	13.6	...	5.7	17.5	16.1	...	13.7	12.2
Polyester	75	TP	2.7	0.26	2.9	7.4[h]	0.9	1.7	5.8	13.5	3.3	5.4
PVC	59	TP	35.9	0.26	3.6	...[f]	1.8	4.4	33.4	...[f]	35.6	22.5

[a] Percent weight loss after 2 h @ 105°C.

[b] After devolatization in air oven for 2 h @ 105°C.

[c] No. = Serial number of liner set by Matrecon; R = Reinforced with a fabric.

[d] Type = Vulcanized (VZ) or thermoplastic (TP).

[e] ELPO = Elasticized polyolefin.

[f] Specimens still under exposure to waste.

[g] Exposure time = 1150 days.

[h] Exposure time - 509 days.

Source: Haxo, 1980a.

TABLE 4-21. RETENTION OF ULTIMATE ELONGATION[a] AND S-100 MODULUS[b] OF PRIMARY POLYMERIC MEMBRANE LINER SPECIMENS ON EXPOSURE TO SELECTED WASTES

Liner data		Compound data			Ultimate elongation, % retention Waste and exposure time in days					S-100 modulus, % retention Waste and exposure time in days			
Polymer	No.[c]	Type[d]	Extractables, %	Original elongation,[e] %	Pesticide 1260 d	HNO_3 1220 d	Caustic 1250 d	Lead 1340 d	Original S-100,[f] psi	Pesticide 1260 d	HNO_3 1220 d	Caustic 1250 d	Lead 1340 d
Butyl	57R	VZ	6.4	70	77	419	142	108	...	...	...	...	...
CPE	77	TP	9.1	405	90	88	115	84	900	114	84	132	72
CSPE	6R	TP	3.8	235	88	83	68	81	645	118	112	199	118
ELPO[g]	36	TP	5.5	665	...[h]	96	...[h]	106	875	...[h]	103	...[h]	110
EPDM	26	VZ	18.2	450	103	79[i]	95	106	360	88	70[i]	109	80
Neoprene	43	VZ	13.9	320	84	...	95	75	460	54	...	96	62
Polyester	75	TP	2.7	575	87	<1[j]	87	90	2585	96	...	110	88
PVC	59	TP	35.9	385	93	...[h]	95	106	960	144	...[h]	170	107

[a] Ultimate elongation = The average of the values in both machine and transverse directions.
[b] S-100 modulus = The average of the values in both machine and transverse directions of the stress at 100% elongation.
[c] No. = The serial number of liner set by Matrecon.
[d] Type = Vulcanized (VZ) or thermoplastic (TP).
[e] Original elongation = Ultimate elongation of unexposed material.
[f] Original S-100 = S-100 modulus of unexposed material.
[g] ELPO = Elasticized polyolefin.
[h] Specimens still under exposure to waste.
[i] Exposure time = 1150 days.
[j] Exposure time = 509 days.

Source: Haxo, 1980a.

completely lost its elongation and that was in exposure to a strongly acidic waste. The CSPE, neoprene, and EPDM liners lost significant elongation in the caustic, lead, and nitric acid wastes, respectively. The CSPE and PVC liners stiffened during exposure to the wastes and the neoprene liner softened. The CSPE crosslinked during exposure and the PVC probably lost plasticizer.

4.3.5.2 Immersion tests

Concurrent with the exposure of the primary liners in the bases of the cells, supplemental membrane liner specimens were hung in the wastes. The effects of exposure were measured by determining the increase in weight, analyzing the exposed specimens and measuring selected physical properties. Details of the procedure followed in conducting the immersion tests are presented in Appendix III-A. The effects of the immersion tests on absorption of the wastes are shown in Table 4-22; the effects upon the elongation of the same materials are shown in Table 4-23.

In these tables, data are presented for 12 membranes based on eight different polymers immersed in eight different wastes from 2 to 2.2 years. Among these membrane specimens were two CSPE membranes, two EPDM membranes, and three PVC membranes. The oily type wastes, which included the lead waste, Oil 104, aromatic oil, and weed oil, represented a range in aromaticity and molecular weight. The weed oil, which is the most aggressive of the oils toward lining materials, is a light aromatic oil. It particularly swelled the CPE and CSPE liners. Oil 104 is a naphthenic and relatively heavy type of oil. It had its most pronounced effect upon the butyl rubber liner. In all cases, there was a variation between the two liners based upon the same polymer. The differences between the two CSPE specimens was the smallest. There were significant differences among the three PVC specimens. The effects of swelling carried into the elongation of the swollen material resulting, in some cases, in drastic reductions in this property.

4.3.5.3 Pouch test

A new test, which was devised during work on the two EPA research contracts, appears to be a promising method for assessing the permeability and durability of membrane liner materials in contact with wastes. At the present time, however, only pouches made of thermoplastic and crystalline sheetings have been successfully fabricated and tested.

In this test, small pouches are fabricated of the membranes to be tested. They are filled with wastes or other test fluids such as salt water, sealed and immersed in deionized water. The permeabilities of the membranes to water and to pollutants are determined by observing, respectively, the change in weights of the bags and the measurements of pH and electrical conductivity of the deionized water. Due to osmosis, water should enter the pouch and ions and dissolved constituents should leave the bag. A schematic representation of the pouch test showing the movement of the various constituents in shown in Figure 4-17.

The initial tests were made with thermoplastic materials because they could be fabricated into pouches with relative ease by heat sealing. Some of these pouches have now been exposed more than 1000 days.

TABLE 4-22. ABSORPTION OF WASTE BY POLYMERIC MEMBRANE ON IMMERSION IN SELECTED WASTES
(Data in Weight Percent)

	Liner number[a]	Data on liner compound		Waste and immersion time in days (d)							
		Type[b]	Extractables, %	Pesticide 807 d	HNO_3 751 d	HF 761 d	Spent caustic 780 d	Lead 786 d	Oil Pond 104 752 d	Aromatic oil 761 d	Weed oil 809 d
Butyl	44	VZ	11.8	1.6	3.8	3.7	0.8	28.7	103.9	31.2	64.2
CPE	77	TP	9.1	12.7	19.9	12.9	1.1	118.9	36.9	226.4	ND[c]
CSPE	6R[d]	TP	3.8	17.3	10.0	9.0	4.3	120.7	49.5	105.2	368.4
CSPE	55	TP	4.1	15.7	10.9	7.7	3.3	116.2	55.0	110.5	347.5
ELPO[e]	36	TP	5.5	0.5	7.6	1.1	0.6	17.0	28.9	29.4	38.1
EPDM	83R[d]	TP	18.2	4.5	4.2	3.1	1.6	24.8	26.5	19.8	84.4
EPDM	91	VZ	23.6	10.4	50.9	12.9	1.3	34.7	84.7	34.2	76.2
Neoprene	90	VZ	21.5	11.4	17.4	12.0	1.5	59.1	26.3	142.6	89.3
Polyester	75	TP	2.7	4.2	6.4	2.0	1.5	7.4	8.5	16.6	14.7
PVC	11	TP	33.9	5.1	22.1	18.1	0.4	-1.5	-10.4	18.5	15.3
PVC	59	TP	35.9	1.0	-6.1	0.9	-0.9	7.4	-0.5	28.9	24.7
PVC	88	TP	33.9	1.6	28.2	14.3	1.1	-5.2	-9.8	14.1	25.2

[a] Liner number = The serial number of liner set by Matrecon.

[b] Type = Vulcanized (VZ) or thermoplastic (TP).

[c] ND = Specimen was lost; some indication that it dissolved in the waste.

[d] R = Fabric-reinforced.

[e] ELPO = Elasticized polyolefin.

TABLE 4-23. VOLATILES[a] CONTENT OF FLEXIBLE POLYMERIC LINERS ON IMMERSION IN SELECTED WASTES

(Data in percent loss of weight)

		Data on liner compound			Waste and immersion time in days (d)							
Polymer	No.[b]	Type[c]	Extract-ables, %	Volatiles (unexposed)[d], %	Pesticide 807 d	HNO_3 751 d	HF 761 d	Spent caustic 780 d	Lead 786 d	Oil 104 752 d	Aromatic oil 761 d	Weed oil 809 d
Butyl	44	VZ	11.8	0.28	3.0	3.8	2.9	6.9	15.3	9.8	3.3	19.2
CPE	77	TP	9.1	0.00	8.6	20.4	8.1	1.6	42.2	5.2	ND[e]	ND[f]
CSPE	6R[g]	TP	3.8	0.29	10.8	10.4	7.6	4.2	3.3	20.2	6.1	50.7
CSPE	55	TP	4.1	0.42	7.9	9.1	7.1	3.6	1.1	10.0	4.8	39.7
ELPO[h]	36	TP	5.5	0.15	0.45	7.2	1.3	0.6	9.5	3.1	1.5	16.4
EPDM	83R[g]	TP	18.2	0.31	4.89	3.1	2.8	2.2	13.9	8.5	4.4	24.1
EPDM	91	VZ	23.6	0.34	15.6	22.6	23.6	1.2	18.5	11.8	4.2	33.4
Neoprene	90	VZ	21.5	0.27	7.26	13.7	10.5	2.9	23.6	6.3	3.9	28.9
Polyester	75	TP	2.7	0.26	1.75	28.0	3.8	1.3	6.1	2.1	3.4	9.5
PVC	11	TP	33.9	0.15	30.9	22.6	18.3	0.6	16.1	2.7	3.6	17.1
PVC	59	TP	35.9	0.26	40.1	10.6	3.0	1.5	12.7	3.3	4.6	16.1
PVC	88	TP	33.9	0.17	3.51	23.2	13.1	1.2	11.5	4.3	3.5	24.1

[a] "Volatiles" content is the loss in weight of a specimen of liner (unexposed or exposed) on air-oven heating for 2 hours at 105°C.

[b] No. is the serial number of liner assigned by Matrecon for identification.

[c] Type of compounds: vulcanized (VZ) or thermoplastic (TP).

[d] Volatiles content of unexposed specimens of liners.

[e] ND = no data obtained because the sample was too badly deteriorated to test.

[f] Immersion sample was lost. Some indication that it dissolved in the waste.

[g] R = fabric reinforced.

[h] ELPO = elasticized polyolefin.

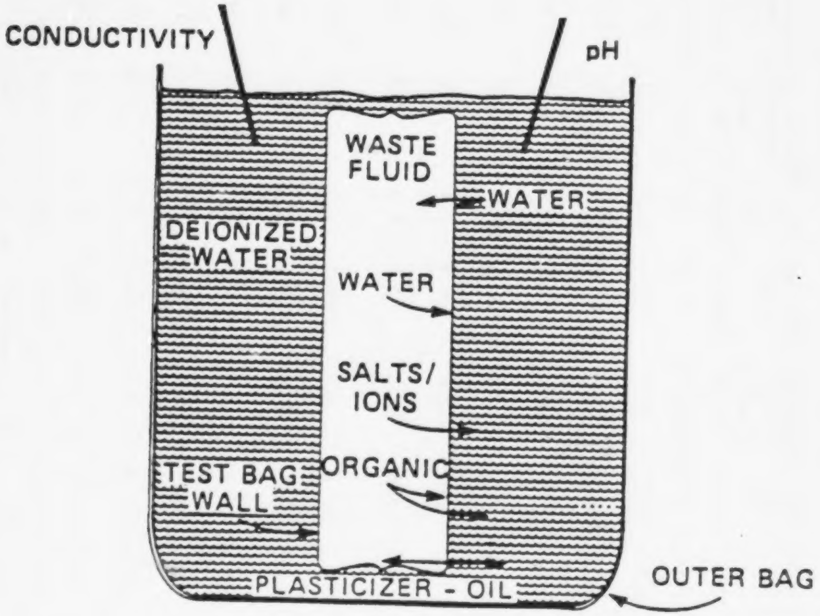

Figure 4-17. Schematic representation of the movements of the mobile constituents in the pouch (bag) test of membrane liner materials.

Bags containing the wastes actually increased in weight, indicating the diffusion of water into the bags through osmosis, as shown in Table 4-24. The long-term tests now show that some ionic material is diffusing through the liners into the deionized water.

Table 4-25 presents the interpolated or estimated times to reach an electrical conductivity of 1000 μmho for slopwater and nitric acid, both of which are concentrated wastes. The data show the greater permeability of the PVC lining materials as compared to CPE, CSPE, elasticized polyolefin, and polybutylene; the latter two are partially crystalline materials.

Table 4-26 presents the results of the thermoplastic membranes tested with 5% sodium chloride solution. The data again show the greater permeability of the PVC with respect to the CSPE and the elasticized polyolefin, which is the most impermeable of the three. These pouches have now been taken out of the test and physical properties of the pouch wall materials have been measured. The results show that, within the 1150 days of exposure, there was some loss in elongation and an increase in the stiffness of the membranes.

4.3.5.4 Tub test

Two samples of a polyolefin liner on exposure in a tub that contained an oily waste failed by cracking at the folds of the sheeting. This membrane was n

TABLE 4-24. RELATIVE PERMEABILITIES OF POLYMERIC MEMBRANE LINING MATERIALS IN POUCH TEST WITH THREE WASTES[a]

Average flux of water into the pouch in grams per square meter per day$\times 10^{-2}$

Polymer	Liner no[b]	Nominal thickness, mils	HNO_3 waste	Spent caustic	Slopwater
CPE	86	22	78.2	26.3	190.7[c]
CSPE	85	33	67.8	36.3	49.2
ELPO[d]	36	23	2.5	3.8	18.4[e]
PB[f]	98	7.5	3.0	7.9	13.6
PVC	19	22	32.4	78.8	325.0
PVC	88	20	64.2	65.9	118.8[g]

[a] Exposure time is 552 days unless otherwise noted.

[b] Matrecon identification number

[c] Pouch failed at 450 days.

[d] Elasticized polyolefin.

[e] Pouch failed at 300 days

[f] PB - polybutylene

[g] Pouch failed at 40 days

TABLE 4-25. PERMEABILITY OF THERMOPLASTIC POLYMERIC MATERIALS IN OSMOTIC POUCH TEST

Time in days for electrical conductivity of water in outer pouch to reach 100 μmho

	Wall of inner bag			Waste in inner bag	
Polymer	Liner no[a]	thickness mils	Extractables, %	NHO_3 waste	Slopwater
CPE	86	20	...	200	420
CSPE	85	33	...	500	510
ELPO[b]	36	22	5.5	300	>1000
PB[c]	98	7	...	600	>1000
PVC	19	20	38.9	70	200
PVC	88	20	33.9	110	160

[a] Matrecon identification number.

[b] Elasticized polyolefin.

[c] PB = polybutylene.

recommended by the manufacturer for service in a waste oil impoundment; however, in a preliminary immersion test, it had appeared to perform satisfactorily with the specific waste. The tub test is described in Appendix III-B.

Specimens for this test were cut from different areas of the exposed liner:

- North side at top of tub.
- North side at waste-air interface.

TABLE 4-26. POUCH TEST OF THERMOPLASTIC MEMBRANES[a]
Pouches filled with 5% NaCl solution

Polymer Liner number[c] Thickness, mils.	CSPE 6R 32	ELPO[b] 36 23	PVC 59 33
Volatiles content of exposed pouch wall, %	8.7	0.38	0.90
Change in weight of pouch plus waste, %	+2.6	+0.71	+0.38
Change in weight of fluid in pouch during exposure, %	+0.95	+0.76	+0.38
Conductivity of water in outer pouch, μmho	585	34	4500
Retention of physical properties, %:			
Elongation	95	100	94
S-100	106	119	120

[a] Exposure time 1150 days (164 weeks).

[b] Elasticized polyolefin.

[c] Matrecon identification number. R indicates the liner is fabric reinforced.

- Under waste at bottom of tub.
- South side of tub at waste-air interface.

The results of the testing of the specimens that was exposed for 43 months are presented in Table 4-27. They show a great variation in the effect of the exposure, the worst being on the north side at the waste-air interface where the losses in tensile, tear, and modulus are large.

The liner that was not exposed to the waste, however, retained its properties during the 43 months of exposures. These results again indicate the importance of location within a waste facility as it affects the liner material.

4.3.6 The Effects of Low Concentrations of Organic Constituents in Wastes

The ability of organic lining materials, such as asphaltic and polymeric membrane liners, to absorb dissolved organic constituents of an aqueous waste, even from dilute solutions, can have a highly significant effect on long exposures upon such liners. This was observed in the case of the asphalt concrete liner below the lead waste which contained a very low concentration of oily material. An experiment was, therefore, performed to demonstrate the effect of minor amounts of an organic chemical upon polymeric membrane liners. Liner materials were immersed in a saturated aqueous solution of tributyl phosphate which contained only 0.1% of tributyl phosphate. The results for a

TABLE 4-27. EXPOSURE[a] OF ELASTICIZED POLYOLEFIN AS LINER OF SMALL TUB CONTAINING AN OILY WASTE

Variation in Location in Tub

Property	Properties of unexposed liner	Properties or percent retention of properties at various locations in tub			
		(b)	(c)	(d)	(e)
Analytical properties:					
Volatiles, %	0.15	1.65	6.2	8.6	8.4
Extractables, %	5.50	7.54	32.7	20.7	23.0
Physical properties:					
Thickness	23 mil	98	112	107	112
✓Tensile at break	2620 psi	84	29	48	37
✓Elongation at break	665 %	80	63	89	83
Tensile set	465 %	92	62	80	76
S-100	925 psi	97	49	63	59
S-200	1020 psi	95	47	61	56
✓Tear strength	380 ppi	94	41	56	48
Puncture resistance:					
Stress	26.3 lb	119	71	68	69
Elongation	0.97 in	144	132	118	116

[a] Forty-three months on laboratory roof in Oakland, CA.

[b] North side at top of tub.

[c] North side at waste-air interface.

[d] Under waste at bottom of tub.

[e] South side of tub at waste-air interface.

group of selected membranes after 17.2 months of immersion are shown in Table 4-28. The data show a great range in the weight gain of the various materials and the corresponding effects upon properties. The weight gains ranged from 0.56% for high-density polyethylene to 107% for a thermoplastic CPE. The effect of crosslinking in reducing swelling is shown by the crosslinked CPE which gained considerably less in weight.

It is recognized that the tributyl phosphate can be used as a plasticizer for a variety of materials, such as PVC. Consequently, it will swell liners of such polymers, but not swell a butyl rubber sheeting, which is less polar and is crosslinked. On the other hand, other organic chemicals with different solubility parameters will affect the polymeric liners differently.

4.3.7 General Discussion of Results

The types of polymeric compounds that have been studied in the above two projects were described in Section 3.4.3. They are based upon the following four types of polymers:

TABLE 4-28
EFFECTS OF EXPOSURE ON SELECTED POLYMERIC MEMBRANE LINERS IN WATER CONTAINING A LOW CONCENTRATION OF A DISSOLVED ORGANIC CHEMICAL[a] FOR 17.2 MONTHS

Polymer Type of compound[b] Liner number Initial thickness, mil	Butyl XL 44 63.0	CPE TP 77 30.0	CPE XL 100 35.8	CSPE TP 55 33.1	PVC TP 59 33.1	HDPE CX 105 31.9
Analytical properties:						
Weight gain, %	21.9	107.2	34.4	31.6	46.2	0.56
Physical properties[c]:						
Final thickness, mil	64	48	41	38	36	31.5
Change, %	+2	+60	+15	+15	+9	-1
Tensile strength, % retention	107	10	63	48	31	88
Elongation at break, % retention	115	155	79	79	89	101
Stress at 100% elongation, % retention	74	6	46	80	28	92
Tear resistance, % retention	...	14	29	39	23	81
Hardness change, Durometer points	-2A	-60A	-20A	-14A	-33A	-1A
Puncture test:						
Stress, % retention	73	20	85	112	48	101
Elongation, % retention	126	127	125	131	133	107

[a] 0.1% Tributyl phosphate in deionized water.

[b] TP=thermoplastic, XL=crosslinked, CX=partially crystalline thermoplastic.

[c] Data for tensile, elongation, S-100, and tear are the averages of measurements made in both machine and transverse directions.

- Vulcanized elastomers, e.g. butyl rubber, neoprene, EPDM, CSPE, CPE, ECO, nitrile rubber, blends.
- Thermoplastic elastomers (TPE), e.g. CSPE, CPE, polyolefins.
- Thermoplastics, e.g. plasticized PVC, PVC with selected elastomers.
- Crystalline polymers (thermoplastic), e.g. LDPE and HDPE.

Note: CSPE is the identification used in the liner industry for chlorosulfonated polyethylene. ASTM nomenclature uses CSM.

Some of the polymers are used in both crosslinked and thermoplastic versions. For example, lining materials of CSPE and EPDM have been manufactured in both crosslinked and thermoplastic versions.

On exposure to fluids, most polymeric materials, whether they are crosslinked or not, will tend to swell and change in some properties. The major factors involved in the swelling of polymeric materials are:

- Solubility parameter.
- Crosslinking of polymer.
- Crystallinity of polymer.
- Chemical stability.
- Soluble constituents in compound.

The solubility parameter is used by polymer scientists to measure the similarity in chemical characteristics of the polymer such as is in the lining material, with a fluid with which it is in contact (Hildebrand and Scott, 1950). For example, a nonvulcanized hydrocarbon rubber, such as natural rubber, will swell and dissolve in a hydrocarbon such as gasoline. On the other hand, a highly polar polymer, such as polyvinyl chloride or nitrile rubber, does not dissolve in gasoline.

Crosslinking a polymer or a rubber reduces its ability to swell in a solvent. Polymer scientists use the swelling of a crosslinked rubber as a measure of the degree of crosslinking: the greater the crosslinking, the less the swelling. This effect is pronounced in such rubbers as CSPE and CPE, liners of which are available in both vulcanized and unvulcanized forms.

Crystallinity of a polymer acts much like crosslinking to reduce the ability of a polymer to dissolve. Highly crystalline polymers, such as high-density polyethylene, will not dissolve in gasoline, even though they are basically similar in chemical composition. Such high density polymers are finding considerable use in containers for a wide range of solvents and chemicals and have recently been introduced as lining materials.

Chemical stability means that the polymer does not degrade on aging which would result principally in reducing its molecular weight causing swelling and dissolving.

Soluble constituents in a polymeric compound can have a strong bearing on the swelling of that material. Most polymers contain minor amounts of solubles, e.g. salt, which are introduced during their manufacture. Soluble constituents can also be introduced into the compound from the compounding ingredients. The swelling is a result of the diffusion of water into the compound.

The effects that the first three factors have on the swelling of liner materials is illustrated in Figure 4-18. The swelling of the thermoplastic type of material in a fluid with which it is somewhat compatible is represented in Curve A, which indicates that the material will continue to swell with time and that no real plateau is reached.

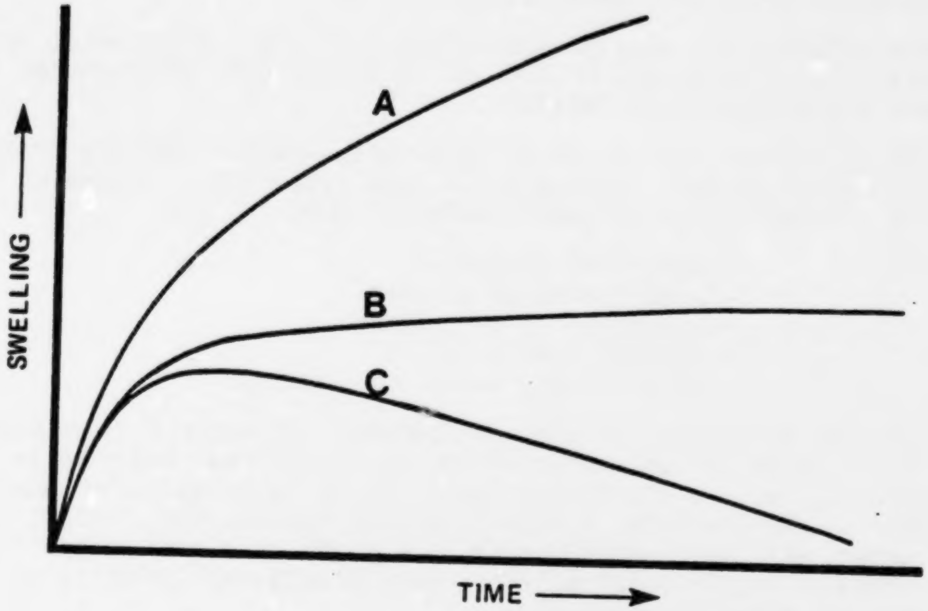

Figure 4-18. Types of swelling of polymeric membranes. A is the characteristic swelling of a thermoplastic polymer whose solubility parameter is close to that of the liquid. B is characteristic of a vulcanized or crystalline material. C is characteristic of a thermoplastic containing a plasticizer.

The swelling of crosslinked material is represented in Curve B, in which the swelling reaches a plateau and changes only slightly with time. The level of the plateau is determined by the degree of crosslinking and by the relative solubility parameters of the waste fluid and the polymer.

Curve C represents a plasticized thermoplastic or a oil-extended rubber in which the plasticizer is leached from the polymer. In this case, there is an initial swelling and then a reduction in swelling. In some cases, there can be a shrinkage of the liner due to the loss of plasticizer or oil. The effects on the physical properties of these exposures have been indicated in the above sections. The swelling will result principally in the softening of the material, possibly in its dissolving, and in increased permeability.

In selecting polymer and rubber compounds for service in a liquid medium, a designer generally selects materials which have low or negligible swell. Swelling of a compound can have adverse effects which will make the product unserviceable. Some of the major effects of swelling generally are:

- Softening.
- Loss or tensile and mechanical strength.
- Loss of elongation.
- Increased permeability.
- Increased potential of creep.
- Greater susceptibility to polymer degradation.

All of these effects are adverse with respect to liner performance. Swelling, therefore, is a valuable indicator of the compatibility of a liner to a waste.

Shrinkage can also be a measure of compatibility for liner compositions that are highly plasticized. For example, in the case of highly plasticized PVC compounds, the plasticizer can leach and diffuse out of the polymer leaving the compound stiff and brittle.

4.4 EFFECT OF WASTE FLUIDS ON ADMIX AND OTHER LINER MATERIALS

As a part of the two liner research programs described in the above section, a variety of soils and admix liner materials were exposed to the same waste fluids. The results of these tests, after limited exposure, are described in the next two subsectons.

4.4.1. Exposure to Municipal Solid Waste Leachate

After one year of exposure to leachate, the asphalt concrete and soil asphalt liners lost drastically in their compressive strengths; however, they maintained their impermeability to leachate. The asphalt binder, which normally hardens on aging in air, became softer indicating possible absorption of organic components from the leachate.

The soil cement liner lost some of its compressive strength; however, it hardened considerably during the exposure period and cored like a portland coment concrete. It became less permeable during the exposure period.

Inhomogeneities in the admix materials, which probably caused the leakage in paving asphalt concrete and soil asphalt liners, indicate the need for considerably thicker liners than were used in the experiment described in this chapter. Thicknesses of two to four inches were selected for the experiment to give an accelerated test and were designed with an appropriately-sized aggregate. The same compositions in the second set of 12 liners did not leak after 27 months of exposure.

The asphalt membranes withstood the leachate for one year, although they did swell slightly. There was no indication of disintegration or dissolving of the asphalt.

4.4.2 Exposure to Hazardous Wastes

Five types of admix materials are being studied in this ongoing project:

- Compacted fine-grain native soil.
- Soil cement.
- Modified bentonite in sand.
- Hydraulic asphalt concrete.
- Membrane based on emulsified asphalt on a nonwoven fabric.

Because of the incompatibility of some of the wastes with particular admix materials, several combinations were deleted. The only liner material that was placed below the acid waste was the hydraulic asphalt concrete. Neither of the two oily wastes was placed on the asphaltic liners; however, the lead waste, which contained a light, oily fraction, was placed on these liners. The performance of the individual admix liners is discussed below:

Compacted fine-grain soil. All of the wastes, except the nitric acid waste, were placed above the compacted fine-grain soil liner. Seepage below all of the liners took place. The amount of seepage was measured and the respective pH, conductivity, and percent total solids were determined. The following observations are made with respect to the seepages through the soil liners:

a. The rate of seepage is 10^{-8} to 10^{-7} cm sec^{-1} which compares favorably with the permeability of the soil measured in the laboratory permeameter. There is some variation in the amount of seepage collected below the liner which may reflect permeability differences, perhaps due to density of the soil.

b. The fluids being collected after more than three years of exposure still continue to be essentially neutral and to have high solids content (mostly salt) and electrical conductivity.

c. There is a downward trend in solids content of the seepages collected under the pesticide and lead wastes, but the seepage under the spent caustic waste continues to be 23% solids.

One set of the soil liners was removed and tested. The permeability of a specimen taken from the cell containing the soil and the aromatic oil waste was determined using a "back-pressure" permeameter (Vallerga and Hicks, 1968). The sample was collected from a depth of seven to ten inches below the surface of the soil, i.e. from that part of the soil which was not penetrated by the oil. The three consecutive values obtained were: 1.83×10^{-8}, 2.43×10^{-8}, and 2.60×10^{-8} cm sec^{-1}. These figures indicate the low permeability of the soil, which had a bulk density of 1.318 g cm^{-3} and a saturation degree of 101%.

Analyses for trace metals were made of the soils which were below the lead waste, Oil 104, and the aromatic oil. The testing included determination of pH and heavy metal content (cadmium, chromium, copper, magnesium, nickel, and lead) on samples collected at different depths in the cells.

With the exception of the liner exposed to spent caustic, the pH of the soil liner was not significantly altered by the wastes. The pH of these samples was in the range of 7.0 to 7.6; the ratio, soil:solution, was 1:2 with 0.01 N $CaCl_2$ being the equilibration solution.

In the case of the spent caustic, the pH values were around 9.0 for samples collected in the first two to three centimeters, which concurs with our previous findings that, over the exposure period of 30 months, the wetting front of the wastes penetrated the soil to a depth of only three to five centimeters.

The heavy metals distribution, as indicated by the analysis, shows, in the case of the lead, only a shallow contamination of the soil. Similar results were obtained on all six heavy metals in the case of the soil below the Oil 104 waste.

Soil cement. All of the wastes except the acid waste were placed on the soil cement liner. No seepage occurred through the liner during the 30 months of exposure.

One set of the soil cement lining materials was recovered after 625 days of exposure to the various wastes and the individual linings were cored and tested for compressive strength. In all cases, compressive strength of the exposed soil cement was greater than that of the unexposed material. There was some blistering of the epoxy asphalt coating which was applied to one-half the surface of each specimen.

Modified Bentonite and Sand. Two types of modified bentonites were used as liners in ten cells. One type allowed somewhat less seepage than the other. There was measurable seepage in seven of the ten cells and one failed allowing the waste (Oil 104) to come through the liner.

Irrespective of the type of waste above the liner, the quality of the seepage was not greatly different among the samples collected. For example, the seepages collected below the pesticide waste on both types of modified bentonite liners were similar.

When the spacers containing the bentonite-sand were sampled, it was found that there had been considerable channeling of the wastes into these liners. There was no channeling at the walls of the spacers.

This type of liner is probably not satisfactory for these types of waste. The use of a soil cover on the bentonite layer to produce an overburden would probably reduce the channeling effect.

Hydraulic Asphalt Concrete. Liner specimens of hydraulic asphalt concrete were placed under four of the wastes. Excluded were the oily wastes.

This lining material functioned satisfactorily under the pesticide and spent caustic wastes, but failed beneath the nitric acid waste. However, the failure arose primarily from the failure of the aggregate which contained calcium carbonate; also, the asphalt was hardened considerably.

In the case of the lead waste, the asphalt absorbed much of the oily constituents of the waste and became "mushy". There was some staining of the gravel below the asphalt liner.

Duplicate cells containing the hydraulic asphalt concrete and the lead waste are still functioning without seepage.

Membrane Based on Emulsified Asphalt and Nonwoven Fabric. This membrane was placed under only three of the six wastes: pesticide, spent caustic, and lead. The acid waste was excluded because of the severe hardening it caused the asphalt, and the oil wastes were excluded because of the high mutual solubility of the asphalt and the wastes.

The asphalt membrane functioned satisfactorily with the pesticide and spent caustic wastes; however, when the cell containing the lead waste was dismantled, the gravel below the liner was wet and stained brown. This result indicates that some seepage took place.

4.5 COMPATIBILITY OF LINER MATERIALS IN WASTE FLUIDS

4.5.1 Introduction

In Chapter 2 various wastes that must be contained are discussed with particular reference to their aggressiveness to different lining materials. In Chapter 3, liner materials which are candidates for the lining of waste disposal facilities are described and discussed with respect to their composition and characteristics.

The compatibility of a liner with a specific waste is one of the first considerations that a designer has in planning a specific landfill site. The designer of a lined waste disposal site must decide which liner material of those he has available can effectively contain the particular waste over the needed length of time. In some cases, the requirement will be for extended lengths of time, such as would be encountered in landfills. The designer must determine what liner materials are compatible with the wastes that must be contained.

It is the objective of this section to summarize some of the information on the wastes and the liners presented in Chapters 2 and 3 and to describe the approach and methodology of determining the compatibility of liners with given wastes.

4.5.2 Screening of Liner Materials Based upon the State-of-the-Art Knowledge

Although the direct experience of compatibility of liners and wastes based upon actual experience is limited, there is a vast amount of information available from the chemical and petroleum industries, soils science, materials science, polymer science and technology, containers industry, coatings industry, etc., from which the engineer and designer can draw to assess compatibility of given materials with wastes. The technology involving the use of materials for the lining of waste disposal facilities is relatively new. It must depend on the experience of other technologies while it is developing and obtaining experience.

In this section the initial screening of liners based upon the available knowledge is described.

4.5.2.1 Characterizing the waste

As has been indicated in Chapter 2, the waste fluids that are in the waste or are leached from the waste can be highly complex materials usually containing water and a wide range of inorganic and organic dissolved constituents. Individually, most of the constituents are well characterized. The difficulty with waste fluids is that they are complex blends containing components that can be toxic and also affect lining materials in a variety of ways. Also, the waste fluid can be highly concentrated and relatively simple, such as would occur in a spill. The analytical capabilities have developed greatly in recent years, therefore, an accurate compositional analysis can generally be made of a waste fluid. The designer must characterize the waste by obtaining an analysis to determine its major constituents. With these data he can make a first estimate of the kind of a liner which must be avoided. For example, oily wastes generally degrade asphalts and many polymeric materials. Soils, though very effective with water, may interact with ionic components such as calcium or, in some cases, some of the organic solvents.

The characterization of the waste should focus on those waste properties which are potentially damaging to liners described in this study. The following is a partial listing of waste constituents which can adversely affect one or more of the liners:

- High pH, greater than 10.
- Low pH, lower than 3.5.
- Oily wastes.
- High temperature.
- Presence of exchangeable ions, e.g. calcium.
- Organic bases and acids.
- Organic compounds, in general.

4.5.2.2 Characterizing the liner materials available

As discussed in Chapter 3, the range of materials which could be used to line disposal sites is large and covers a wide range of types, from soils and admixes to membranes of many kinds. As the soil at the site would probably be a candidate liner, it should be thoroughly investigated with respect to its character, not only as to permeability, but also with respect to compatibility with the waste that might be placed on it.

The effects of various salts and chemicals upon soils are known from the agricultural science and, to some extent, from chemical science. From the polymer industry there is considerable information available on the use of polymeric materials for the lining of many pipes, reactors, gaskets, etc. which function in nonaqueous media, acids, bases, etc. Generally, these liquids are simple, that is the number of constituents are few. However, there is wide experience with handling these various materials. Many plastics and rubbers are used in outdoor applications and much information is available with respect to their durability and weatherability. Considering the available liner materials, it is quite possible that some can be eliminated when considering the waste that must be contained.

4.5.2.3 Matrix of liner materials-waste compatibilities

Out of experience to date, matrixes of wastes and liners can be considered to indicate the general compatibility of some of the materials. An example of this is in Table 4-29 which shows the range of types of liner materials and a variety of industrial and hazardous wastes. In all cases, neither the types of liner materials nor the types of wastes are specific. Each has a range of

TABLE 4-29. LINER-INDUSTRIAL WASTE COMPATIBILITIES[a]

Liner material	Caustic petroleum sludge	Acidic steel-pickling waste	Electro-plating sludge	Toxic pesticide formula-tions	Oil refinery sludge	Toxic pharma-ceutical waste	Rubber and plastic
Soils:							
Compacted clay soils	P	P	P	G	G	G	G
Admixes:							
Asphalt-concrete	F	F	F	F	P	F	G
Asphalt-membrane	F	F	F	F	P	F	G
Soil asphalt	F	P	P	F	P	F	G
Soil-bentonite	P	P	P	G	G	G	G
Soil cement	F	P	P	G	G	G	G
Polymeric membranes:							
Butyl rubber	G	G	G	F	P	F	G
Chlorinated polyethylene	G	F	F	F	P	F	G
Chlorosulfonated polyethylene	G	G	G	F	P	F	G
Ethylene propylene rubber	G	G	G	F	P	F	G
Polyethylene (low density)	G	F	F	G	F	G	G
Polyvinyl chloride	G	F	F	G	G	G	G

[a]Stewart, 1978. G = Good, F = Fair, P = Poor.

compositions and characteristics. A rating of "good" indicates that the combination is probably satisfactory; "fair" indicates the combination should be tested, and "poor" indicates the combination should be avoided. This table functions only as an initial guide and, in many cases, specific combinations of liner materials and wastes must be tested before selecting acceptable liner materials. This is the subject of the next section.

4.5.3. Testing of Specific Combinations of Liners and Wastes

As indicated in the previous section, knowledge of the wastes to be contained and the lining materials available can be used to make an initial screening of specific lining materials which might be suitable for containing the wastes. In some cases this knowledge may be sufficient to make a choice, particularly if the waste does not contain components aggressive toward liners. Generally, a compatibility test should be performed before a specific liner is selected.

4.5.3.1 Sampling and analyses of wastes for compatibility tests

In order to run accurate compatibility tests of lining materials, a representative sample of the waste must be obtained. In as much as wastes are generally highly complex and heterogeneous, there is a major problem in obtaining representative samples. In some cases samples of the specific waste may not be available and similar types of wastes must be used. Furthermore, consideration must be given to the fact that over the period of time that an impoundment may be operating, there may be a change in the composition of the wastes.

4.5.3.2 Compatibility testing of soils

Testing of candidate soils for use as the liner for a specific waste impoundment is necessary to determine chemical sensitivity to the waste. The effect of the waste upon permeability of soils is the most relevant as indicated in Section 4.2. A recommended test method is described in Appendix III-C.

4.5.3.3 Polymeric materials

Individual types of tests have been found useful in assessing the effects of the wastes upon lining materials. These are:

- Immersion test.
- Tub test.
- Pouch test (limited to thermoplastics and crystalline materials).

The first two of these tests are described in detail in Appendixes III-A and III-B, respectively.

Immersion Test. In this test samples of the specific membrane liners are immersed in the waste and the effects of the immersion upon the weight and dimensions of the liner specimens and a selected number of physical properties are measured as a function of immersion time. By immersing the samples totally in the waste fluid, a somewhat accelerated test is generated. Further acceleration can be effected by increasing the temperature somewhat. However, the closer the temperature and exposure conditions are to actual service, the more reliable the results will be. Also, the longer the test can be run, the more reliable it will be. These types of tests should be initiated early in the design phase of the waste facility. An exposure period of twelve months is desirable. Samples can be withdrawn at one, two, four, etc., months to assess the effect as a function of time.

Pouch Test. This test was designed to measure the permeability of polymeric membrane liner materials to water and to dissolved constituents of the wastes. A sample of the waste is sealed in a small pouch fabricated of the liner material under test which is then placed in distilled or deionized water. Measurements are taken periodically to determine the extent of movement of water into the membrane and/or leakage of waste into the water. A concentration gradient is created by the deionized water on one side of the membrane and the waste on the other side. This test environment results in the movement by osmosis of water and ions and other dissolved constituents through the membrane due to the differences in concentrations on either side of the membrane. Changes in liner materials are observed and later physical properties are tested. At present, this test is limited to thermoplastic and crystalline membranes; however, it can be used to asses the compatibility of wastes with these materials.

Tub Test. The purpose of this test is to evaluate flexible membrane liner materials under conditions which simulate those that occur in actual service. The effects of exposure to the sun, temperature changes, ozone, and other weather factors can be evaluated as well as the effect of a given waste on a specific liner. The fluctuation of the level of the waste is particularly significant in that a horizontal section of the liner is subjected to the effects of both the waste and weather. This alternating of conditions is especially harsh on liner materials and is usually encountered in the field.

4.6 FAILURE MECHANISMS AND ESTIMATING SERVICE LIVES

An important factor in selecting liner material for a given disposal facility is to match the required life of the waste impoundment with the estimated service life that can be anticipated for a given liner in the particular exposure condition. It is recognized that there can be a range in the lives that are needed. For ultimate disposal of a waste, very long times are required during which a liner must maintain its integrity and function as designed. On the other hand, for temporary holding ponds, much shorter lives are satisfactory.. Furthermore, the life of a liner will depend upon the waste which it contains.

In order to make estimates of the service lives, it is necessary to know how the liner system might fail. In Section 4.2 the various failure mechanisms relating to clay soil liners are described and discussed. The effects of a variety of wastes on soils are described with particular reference to their loss in permeability and in strength resulting from the effects of chemical species on the soils.

The effects of various wastes on polymeric membrane and admix liner materials are described in Sections 4.4 and 4.5 respectively. Some of the effects appear to be severe enough to cause a liner to fail if the exposure is sufficiently long.

The experience in the field with membrane type liners and liners in general has been primarily for reservoirs and other water containment facilities. The failure type mechanisms that have been encountered are described by Kays (1977). An amplification of the subject of failure mechanisms and estimating service life will be forthcoming in revisions of this Technical Resource Document.

This section describes and discusses the categories and characteristics of the failures of liners in the service environment. The objective of this section is to enable the user of this manual to understand and identify liner failures and the events leading to failure. The three major categories of liner failure that will be discussed in this subsection are physical, biological, and chemical. Table 4-30 is a listing of the principal failure mechanisims in liners.

Failure of liners include problems in the subgrade, the lining material itself, forces of weather and aging, and problems imposed by operating procedures on condition. The problems in subgrades are related to compaction, differential settling, slope sloughing, built-up hydrostatic and gas pressures. Failures may be induced by chemical and/or physical circumstances. Chemical compatibility failures are a function of the waste-liner combination, while physical failures are more often subgrade related.

4.6.1 Physical Failures

There are several modes of liner failure due to physical processes and stresses, each of which is described in the following paragraphs. Each particular failure mode may or may not apply to every type of liner. However, notable examples will be presented where warranted.

TABLE 4-30. FAILURE CATEGORIES

Physical	Biological	Chemical
Puncture	Microbial attack	Ultraviolet attack
Tear		Ozone attack
Creep		Hydrolysis
Freeze-thaw cracking		Ionic species attack
Wet-dry cracking		Extraction
Differential settling		Ionic species incompatibility
Thermal stress		Solvents
Hydrostatic pressure		
Abrasion		

4.6.1.1 Puncture

Puncture failure would most commonly occur in membrane liners; however, such failure can occur in the other types of liners under specific circumstances. Puncture failure of membrane liners due to sharp angular rocks in the subgrade that have become exposed to the liner because soil fines migrated downward over time is a major concern. Puncture from operations, man or vehicular, is of concern but can largely be mitigated through good operation procedures. Burrowing animals and hoofed animals seeking water can also cause puncture.

4.6.1.2 Tear

Tear failure is similar to puncture failure in its occurrence. Because of a membrane's relative thinness compared to soils, clays, asphalts and other liners, its resistance to failure in that dimension is correspondingly reduced. Localized structural tear failure can result from several stress-relaxation-stress cycles in which the liner is losing strength or it stretched with each cycle. Tear, like puncture, can occur due to operations or animals.

4.6.1.3 Creep

Creep is the common term used to describe increasing deformation of a material under sustained load. The main factors which influence creep failure are material microstructure, stress level and temperature. The significance of this type of failure is that it is difficult to detect and control. Creep can occur with any liner material.

4.6.1.4 Freeze-thaw cracking

Cycles of freezing and thawing cause material cracking which leads to failure by volume expansion of liquids in pore spaces during freezing. This expansion increases pore space volume and the accessibility of liquids to the pore space volumes. In addition, the freeze-thaw cycle will not be a localized failure at a facility, but will occur throughout. Proper planning and design is essential to mitigate this type of failure in areas where freezing is a major concern.

4.6.1.5 Wet-dry cracking

This mode of failure is most commmonly found when clay liners are used. The wet-dry cycles cause alternate expansion and shrinkage of clay liners which decrease the strength of the liner and increase its overall effective permeability. Because soil materials have poor tensile strength, the shrinkage caused by drying is highly disruptive to the cohesive structure of clays. Other liners are adversely affected by wet-dry cracking, but to a lesser extent.

4.6.1.6 Differential settling

Differential settling can damage all liners. This problem is best mitigated with a thorough geologic analysis prior to site selection and careful subgrade design and construction. Differential settling is a localized structural stress phenomenon and the greater the thickness and elasticity of the liner, the greater the tolerance range for differential settlement.

4.6.1.7 Thermal stress

Thermal stress results from differential temperatures through a material or when temperature change is sufficent to cause a phase change in a material. This temperature change (especially in polymeric membranes) can cause volume changes by thermal expansion (or contraction) as the case may be, or by phase changes. Thermal stress may also become significant in light of the different reaction rates produced by individual components of a composite material. Phase changes in solid materials caused by heat, generally cause stress because different phases usually have different volumes per unit weight. Thermal stress can be controlled or tolerated by allowing for expansion or contraction in design, stress relief, or an acceptable range of variation. However, if the stress is great enough, cracks will occur. All asphalt liners are highly susceptible to temperature. Polymeric membrane liners are also temperature sensitive, but to a lesser degree.

4.6.1.8 Hydrostatic pressure

Hydrostatic pressure is of concern when the structural support of a subgrade or base material is lost by piping, sinkholes, oxidation of organic material, settlement, etc. The effect of hydrostatic pressure exerted beneath a liner, which is due to inadequate drainage below the liner, is discussed in Chapter 5.

4.6.1.9 Abrasion

The continuous or near continuous action of abrasion on a liner has a significant wearing effect over time. Windborne abrasion is a serious consideration. In arid regions, sand particles carried by the wind have a sandblasting effect on the liner. Liners with high abrasion resistance must be specified, or a protective cover must be placed on the exposed berms. Runoff entering the pond from the surrounding topography may contain sticks, branches, rocks, and other debris which could abrade, tear, or even puncture the liner. Construction of a diversion channel to handle runoff will avoid the potential problems.

4.6.2 Biological Failures

The major emphasis on biologically induced failure is microbial attack in which the microbes "eat" the material and damage or destroy its structural integrity and low seepage characteristics. Particularly susceptible to biological attack are the plasticizers that are used in some polymer compounds. Bactericides are sometimes used to counteract this type of failure.

4.6.3 Chemical Failures

Because organic and inorganic chemicals constitute a great majority of the hazardous wastes to be contained in lined waste impoundment facilities, chemical failures are of great importance and significance. The following paragraphs describe the various types of chemical failures.

4.6.3.1 Swelling

The most serious chemical effect to polymeric liners at waste disposal facilities is that of swelling which is discussed in detail in Section 4.3.7. Potentially, sufficient swelling can cause loss in strength, elongation, creep and flow, and loss in puncture resistance. Failures of these types are most apparent when the liner is in direct contact with the wastes.

4.6.3.2 Extraction

Liner materials such as polyvinyl chloride which contain large amounts of monomeric plasticizer are highly susceptible to extraction of the plasticizer. Such extraction can result in embrittlement and shrinkage and possibly breakage of the liner. This effect is also discussed in Section 4.3.7.

4.6.3.3 Outdoor exposure

Exposed polymeric linings can be subject to failure from heat and infrared, ultraviolet light, oxygen, ozone, and moisture. The factors generally operate in combination, with the presence of oxygen and moisture being the major contributing factors. Failure of the liner generally occcurs from embrittlement, shrinkage and breakage. Ozone can cause cracking of many polymers, particularly those which contain some unsaturation. Failures of this type occur in areas where the rubber sheeting is stretched.

Considerable information is available on the durability and service lives of exposed lining materials in which the principal environmental conditions are ultraviolet light, oxygen, ozone, heat, and wind (Strong, 1980).

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CHAPTER 5

DESIGN AND CONSTRUCTION OF LINED WASTE FACILITIES

5.1 INTRODUCTION

This chapter discusses the planning, design, and construction of lined facilities for waste storage and impoundment with particular regard to the design and construction of the lining. The discussion in this chapter provides site selection background, even though it is assumed that the site has been selected, and presents design and construction guidelines of the best available engineering practice in liner technology. A detailed description of the installation of flexible membrane liners and the leachate collection systems is presented in Appendixes IV and V, respectively.

A critical aspect of each liner installation is adequate quality control of materials and workmanship. Ideally, the quality control function would be performed for the owner by a party independent of the liner manufacturer, fabricator, installer, and earthwork contractor. That party should be responsible only to the owner of the facility. The owner should then be able to certify to a regulatory agency that the facility was constructed as planned. Often a quality control function is not included as part of a design and construction program. As a minimum, the owner or person ultimately responsible for the operation of the lined facility must check the quality of the materials and installation workmanship on the job site before accepting the finished product.

In this chapter the design and construction of liners of the following materials will be described:

a. Soils and clays

b. Admixed materials

c. Flexible membranes

d. Sprayed-on, soil sealant, and chemisorptive materials.

The design and construction of the final covers is discussed in a separate Technical Resource Document, SW 867 (Lutton, 1982).

Lined impoundments have several specific end uses, each with its own particular objectives and period of performance. A lined waste impoundment can be a pond, a landfill for hazardous waste, or a sanitary landfill. The reasons for the use of a liner or liners range from groundwater protection to resource recovery to improved reliability. Depending upon the type(s) of waste, the period of containment, the surrounding climatic conditions, the available native soil and geologic structure, the geohydrologic characteristics, and several other factors, the selection, design, and construction of a lined waste impoundment can easily become a complex and intricate procedure. The waste characteristics significantly influence the choice of liner type, as does the purpose of the containment. If the facility is short term or temporary in its function, i.e. the waste is to be stored for a period of time and then excavated or transferred elsewhere, the selected liner component will be quite different from a facility which is proposed for permanent disposal of waste.

5.1.1 Types of Constructed Impoundments

The three major categories of new impoundment installations are as follows: (1) totally excavated; (2) filled; and (3) combination. Excavated impoundments are those which are dug from a surface (Figure 5-1) such that the major portion of the capacity is below the grade of the surrounding land surface. Filled impoundments are built up above grade such that the large majority of the capacity is at an elevation higher than the immediate surroundings. Combination impoundments result when material is both excavated and filled (Figure 5-2).

Excavated impoundments are found primarily in relatively flat areas where loose soil of a suitable nature (alluvium, for example) exists. As soil is excavated, some may be left at the perimeter of the excavation to be used for berm construction and levelling. The remainder of the material may be used for daily cover if the impoundment is a municipal solid waste landfill, for general grading, or for fill in other construction activities.

In some instances, bedrock is encountered before excavation of the impoundment is completed, thus necessitating blasting and rock removal. The economics of storage, containment, land, excavation difficulty, material use, and other considerations must be systematically analyzed before selecting the overall impoundment design.

Filled impoundments are frequently constructed at sites with bedrock near or at the surface because the cost of blasting and excavating precludes excavated impoundments in all but extreme cases. High groundwater table and capillary zones are other frequent reasons for this type of construction. Where local geologic considerations preclude the economical construction of excavated impoundments, the desirable earth materials (sand, silt or clay) for berm and bottom construction are often hauled in from off-site locations. A special type of filled impoundment is one built in an existing valley. An earthen dike is constructed between the valley walls and across the valley floor (Figure 5-3). Earth materials are used to prepare the sides and bottoms of the impoundment prior to liner installation. Care must be taken in valley span facilities to account for both surface and subsurface runoff and take appropriate measures to manage the flow.

Most impoundments can be classified as combination excavation-fill impoundments. A balanced cut-fill project will usually result in the best economics. The designer should recognize that the upper 3 to 12 inches of topsoil should

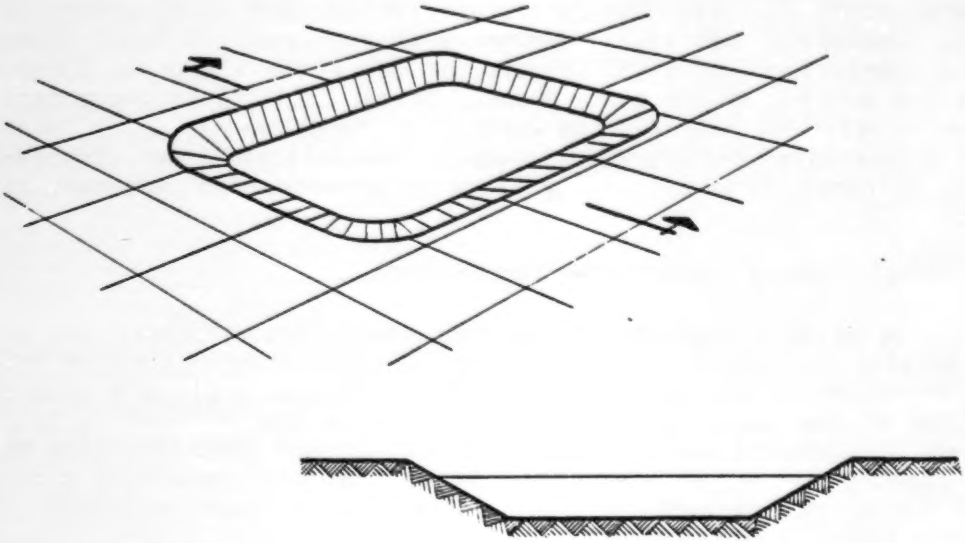

Figure 5-1. An excavated impoundment (EPRI, 1979).

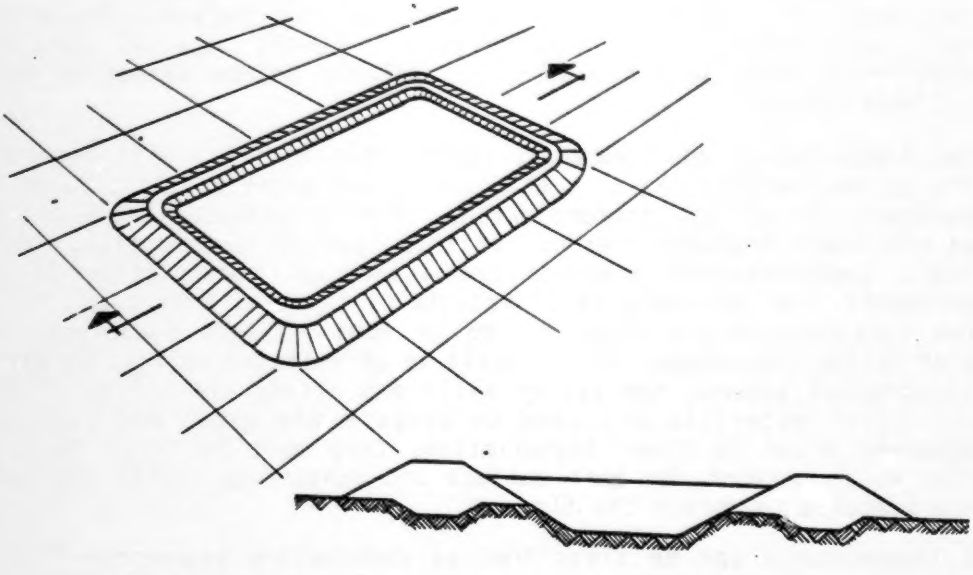

Figure 5-2. Diked pond partially excavated below grade (EPRI, 1979).

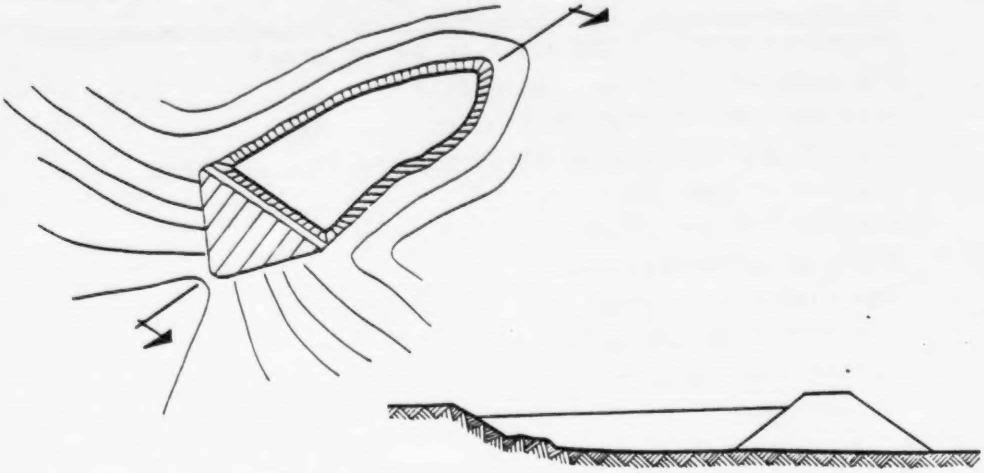

Figure 5-3. A cross-valley pond configuration (EPRI, 1979).

be removed for use elsewhere and that the soil excavated may shrink 5 to 20 percent between excavation and placement in an engineered fill.

The excavated material will be used to build side walls, berms, basal areas, and for miscellaneous construction needs. The fill soils are molded by the engineering contractor to the desired grades, and physical and mechanical characteristics established by the project plans and specifications. If the material at the site within the confines of the planned impoundment meets the needed design/construction constraints, then time and money can be saved by using the immediately available material in subsequent construction activities.

5.1.2 Site Planning Considerations

The construction, successful completion, and desired finished characteristics of an impoundment can be greatly influenced by the site chosen for its location. The selection of a site depends upon many factors. Table 5-1 is a list of factors which should be considered in the site planning/construction process. The design of most impoundments is controlled by the type of waste to be impounded and the type of facility which the impoundment will serve. Table 5-2 provides a checklist of important data the designer must assemble and evaluate before beginning to design a waste disposal facility at a specific site.

5:2 DISPOSAL FACILITIES WITH LINERS OF SOILS AND CLAYS

Unlike other engineering works in which manufactured structural materials with code-prescribed properties are used, in the case of soil-liner construction there is often an economical need to use the existing in-place soil material. This is the situation if a prior analysis has proven the soil material to be an acceptable material for being "improved" as a liner.

TABLE 5-1. FACTORS TO BE CONSIDERED IN THE SITE PLANNING/ CONSTRUCTION PROCESS

- Characteristics of the waste to be impounded
- Characteristics of soil materials
- Subgrade characteristics from soil borings
- Desired characteristics of bottom and side surfaces
- Location of bedrock
- Stability of materials
- Drainage considerations
- Impoundment dimensions
- Wind direction and velocity
- Ambient temperature
- Gas venting
- Local vegetation
- Floor considerations
- Berm width requirements
- Inflow/outflow/overflow conveyances
- Monitoring/leak detection systems
- Cover material availability/characteristics
- Proximity to major waste generators
- Proximity to residential and commercial areas
- Coupon testing and evaluation, if applicable
- Weed control
- Location of groundwater and capillary zones
- Presence of indigenous burrowing animals
- Fencing requirement and access

5.2.1 General Discussion

Because of soil variability and the scale of the operation in designing and constructing a soil liner, relatively more flexibility must be provided by the designer in the specifications required. These specifications should be both essential and operational and should be stated in terms of performance required from the soil liner and in terms of methods of achieving the required performance.

A very important feature of the construction operation of a soil liner is the inspection of the adequacy of the work performed. This is done by visual observation and testing. Although a large amount of experience has been accumulated in constructing similar structures, e.g. dams, canals, embankments, etc. relatively little is known about the construction of soil liners of large areas; accordingly, the quality control function should be given a high priority. The inspection work should be performed during construction and the amount of effective inspecting work will depend on the ability of the quality control team, its cooperation with the construction group and the capacity of the contractor to "learn while doing" and improve his performance.

TABLE 5-2. RELEVANT BACKGROUND INFORMATION HELPFUL DURING SITE SELECTION PROCESS

USER INFORMATION

Owner's name
Owner's location and telephone number
Design engineer
Operator's name
Site and facility location

METEOROLOGICAL DATA

Temperature - high, average, low
Wind direction, velocity
Precipitation - snow, hail

PROCESS DATA

Waste description
Relevant waste characteristics
pH
Temperature
Composition of waste
% Solids
Quantity
Unusual variations, e.g. loading, chemicals, temperature

FACILITY NEEDS AND CHARACTERISTICS

Capacity
Dimensions
Longevity
Harvesting or reclamation program(s)
Aeration program - equipment and methods
Waste flow variation and discharge velocity
Inlet system
Outlet system
Venting systems
Lining penetrations
Regulatory agencies
    Names
    Addresses
Monitoring requirements

To assist the inspection operation, a field laboratory should exist, or better, access to a qualified laboratory should be available. The effort should be such that, at any time during the construction of the soil liner, a clear qualitative assessment can be made as to whether the work performed complies with the specification.

Heterogeneity of soil is the rule rather than the exception; it is "the nature of the beast". The design specifications, based on all pertinent information, must provide the contractor who performs the site improvement (the construction of the soil liner) with all needed information. The specifications should state clearly the working procedures for every type of soil or unit so that the end result will be a uniform soil liner.

The working procedures indicated in the design specifications for a particular soil unit normally would be easy to observe if the soil cover were to have a uniform moisture content and density characterization in the undisturbed state; oftentimes, though, there is a soil intraunit heterogeneity which can escape observation during the reconnaissance investigation.

The construction of a soil liner is the field operation in which in-place or imported soil material is compacted and remolded such that the seepage through it is restricted. The most important purpose in producing such a blanket is to impede waste-effluent flow. Since this is done by soil densification, the contractor and the quality control should have to provide evidence that:

a. The design density is achieved.

b. At these density specifications, the soil has indeed the designed flow properties.

The highest priority of the quality control has to be in checking item (a); the quality control group should cooperate fully with the designing group in assisting the investigations in item (b).

The operational specifications refer to the following:

a. The depth of the soil liner.

b. The moisture-content of the soil to produce the desired density.

c. The depth of the unit-layer to be compacted at one time.

d. The number of passes of the compacting implement over one unit-layer.

e. The weight of the compacting implement.

f. The type of compacting implement.

g. Possibly the trade-name of the compacting implement.

All these operational specifications have to be rigorously observed by the constructing team.

5.2.2 Testing of Soil for Selection and Design of Liner

The principal requirements that a soil must meet for use as a liner for waste disposal facilities are:

a. Low permeability to water and waste fluids.

b. Little or no interaction with the wastes which might increase permeability.

c. Absorptive capacity for pollutant species.

d. Strength initially and after contact with waste fluids to maintain slope stability.

In addition to the above principal soil requirements, the history of the candidate soil must be investigated to determine its prior use or exposure to hazardous, toxic or other undesirable elements which might affect the function of the waste impoundment facility. For example, monitoring the performance of a liner constructed with soil contaminated with a toxic substance would very likely show that substance below the liner at some point in time, even though the liner was functioning properly, and that particular substance had never been placed in the impoundment facility. This study of the subgrade soil may require chemical analysis of the soil and the pore water therein.

This subsection is concerned with the laboratory testing of the candidate soils for possible use as a liner at a particular waste disposal facility. This testing should be incorporated in the soil selection process and in designing of the liner to insure the adequacy of the soil selected and to form the basis of the design.

5.2.2.1 Atterberg limits

The determination of liquid and plastic limits is essential for both classification purposes and behavioral assessments (Section 3.2.3.1). The liquid limit of soils should be determined by ASTM D423 and the plastic limit and plasticity index by ASTM D424 for classification purposes.

If reasons exist to suspect that the soil is sensitive to the chemical composition of the waste fluid, one may wish to perform a compaction study. Two variables should be considered: (1) the seasoning period, i.e. the length of time in which the soil is cured with water and, (2) the chemical composition of the fluid used. If, in comparison with distilled water, a 0.01 N $CaSO_4$ solution produces drastic changes in plastic properties, a waste leachate should be obtained and used in determining the limits. The generated results should constitute the starting point for the investigation of flow, volume change, and strength characteristics of soils.

5.2.2.2 Determination of moisture-density relationships

In different sections of the manual, e.g. Sections 3.2.2, 3.2.3, and 4.2, it is emphasized that soil compaction or densification in the field should be performed in order to obtain a soil blanket with low permeability. In the case of soils with sensitive structures, the low permeability is achieved not as much through densification as by a structural improvement of the soil. This aspect of the problem raises serious doubts about the terms "densification" or "compaction". Indeed, since the in-place soil is the material which is improved in a soil liner, the improvement is done by "remolding and recompacting" the soil.

To reproduce this procedure in laboratory condition, advantage has been taken of available information regarding the effect of compactive effort and of different compaction methods on soil structure and flow properties. Accordingly, a minimal test program should comprise both static and kneading compaction procedures. The research should be concentrated on the "wet-of-optimum" which has greater flow-sensitivity implications for the soil. However, the degree of sensitivity can be ascertained only when permeability tests are conducted on soil samples which have been compacted at known combination of density and moisture content. Thus, it becomes clear that the two aspects (compaction and permeability) are related and compaction efficiency should be investigated as a comprehensive test program.

To generate a moisture-density relationship, we recommend ASTM D698 and ASTM D1561. Additional information can be obtained by comparing the results obtained by ASTM D1557 with those obtained by the low-compacting effort method, ASTM D698. When using the kneading compaction method, ASTM D1561, it is important to vary the thickness of the compacted layer and/or the amount of compactive energy per layer.

5.2.2.3 Permeability to water

A clay soil's permeability (K) is a numerical value representing its ability to transmit fluid. From Darcy's law for liquid flux through a porous medium, it can be seen that a soil K value is independent of the volume of soil, the volume of fluid passing, and the hydraulic gradient moving the water:

$$J = \frac{Q}{A} = -K\Delta H$$

where:

J = flux of a fluid ($cm^3 cm^{-2} s^{-1}$)

Q = flow ($cm^3\ s^{-1}$)

K = permeability coefficient ($cm\ s^{-1}$)

ΔH = hydraulic gradient

A = cross-sectional area of flow (cm^2)

and since:

$$Q = \frac{V}{t}$$

where:

V = volume of fluid (cm^3)

t = time (s)

therefore:

$$K = \frac{-V}{At\Delta H} .$$

Darcy's law assumes direct proportionality between the hydraulic gradient (ΔH) and the flow rate (Q) where flow is laminar. Accordingly, any change in the permeability coefficient (K) will represent a change in the porous media.

For comparison of a clay's permeability to different fluids, the fluid's viscosity and density must be incorporated into Darcy's law along with the gravitational constant. So adjusted, the permeability coefficient is changed to the intrinsic permeability coefficient (IPC):

$$K' = K \frac{n'}{G}$$

where:

K' = IPC expressed in the c.g.s. system as cm^2

K = permeability ($cm\ s^{-1}$)

n' = kinematic viscosity ($cm^2\ s^{-1}$)

with

$$n' = \frac{n}{\rho}$$

n = viscosity ($g\ cm^{-1}\ s^{-1}$)

ρ = density ($g\ cm^{-3}$)

G = gravitational constant, 981 $cm\ s^{-2}$ at 45° latitude.

Viscosity normalizes a fluid's resistance to flow due to its cohesiveness, while the fluid's density values normalize the effect of gravity on its flow. Use of IPC values permits the addition of K' values where there is more than one fluid flowing through a soil.

A representative sample of the spectrum of pure organic liquids often placed in waste impoundments was investigated to determine their effects on the permeability of clay liners. Results of this study are reported in Chapter 4. Central to these tests was the development of a constant pressure permeameter suitable for permeability measurements of compacted clay liners subjected to organic chemicals. The test apparatus and methods for the permeameter are given in Appendix III-C.

Several factors not incorporated into these laboratory tests enter into a clay's overall permeability. Sherard et al. (1963) listed the primary factors determining "effective overall permeability" of a layer as: continuity, regularity, thickness, and characteristics of interbedded layers or lenses. A laboratory determination of permeability cannot take into account this type of variability in a clay liner. It attempts to characterize only a homogenized sample of the clay soil. Nevertheless at this point we must rely on laboratory tests.

5.2.2.4 Permeability to waste liquids

The previous subsection presented the permeability of water through a clay or soil medium. This section is concerned with the permeability of soils to waste fluids. This topic and related topics have been discussed in detail in Subsections 2.2.5, 3.2.2, and 3.2.3, as well as Sections 4.2 and 4.3. These sections stated that the interaction of clays and soils with various waste fluids can be adverse, resulting in the loss of the structural and chemical integrity of the liner. The range of waste fluids that have been tested is by no means extensive or exhaustive. Much research work remains to be done related to individual wastes not yet tested. Before finalization of design and initiation of construction, compatibility testing of the expected wastes to be contained with the proposed liner types should be conducted. As a minimum some pilot or laboratory scale permeability testing with wastes should be conducted. Presented in Appendix III-C is an experimental permeameter which can be used for accelerated testing.

5.2.2.5 Determination of soil strength characteristics

It is generally recognized that testing of a soil specimen in the laboratory with the purpose of determining its strength characteristics should simulate the failure possible to occur in the field. Of particular significance are pore-water pressure changes and their relation to soil strength. If field volume changes are prevented, pore-water pressures can develop in the soil. The simple situation in which the soil accepts water under a certain confinement and then deforms in shear without change in volume, can be duplicated in the laboratory in a consolidated-undrained triaxial compression test (CU-test). For this purpose, ASTM D 2850 should be used with the provision that volume changes are permitted while the sample is under σ_3 loading (chamber pressure).

Despite its tremendous advantages, triaxial testing has its limitations. One of the important drawbacks is that in the apparatus the sample can reach only a limited strain, sometimes considerably below the values of strains required in slope stability analysis; this is particularly true with cohesive soils. On the other hand, it may be more meaningful to perform an extension rather than a compression test since this condition seems to reproduce slope failure better.

Apart from the triaxial technique, either a direct shear or a vane shear apparatus can be used to determine soil strength characteristics. The most important fact to be remembered is that the possible failure mechanism must be reproducible in the laboratory.

The strength properties of clay soils are important not only with regard to slope stability, but also with regard to the task of compacting the soil to a particular desired density. It has been suggested that, in the case of plastic soils, if the moisture-density relation is such that a California Bearing Ratio (CBR) value lower than five is obtained, the roller will do a poor compacting job since the soil will tend to "ball up" and the roller may not "walk out" properly (Burmister, 1964).

In the design of a sloped soil liner, the first approach should be to compact the soil using the parameters which are considered to generate the least permeable soil, i.e. without consideration of strength properties. If, by using this procedure, a critically weak soil is generated (safety factor less than 1.2), then ways to improve strength properties should be investigated by testing; the main task should be to ascertain the most economical way of improving the strength of the soil liner associated with the least detriment to soil permeability characteristics.

The exact conditions which have to be observed during the field compaction to obtain the highest safety factor cannot be explicitly stated; Seed et al (1960) wrote: "Since the influence of these factors are often conflicting - for example, a flocculated structure promotes high strength at low strains but it also promotes high expansion characteristics - a variety of patterns relating undrained strength after soaking to initial composition can be obtained for various types of soil."

The observations described in this section with regard to the effect of varying compaction conditions upon strength should be considered only as indicative of what may happen with any particular soil. In this discussion, the emphasis is deliberately placed on the effect of soil structure on strength; this is not to say that chances of encountering a structure-sensitive soil are very large. Probably, the reverse is true. The over-estimation of structural effects in our discussion is made because:

a. Structural aspects are relatively more important in the group of cohesive soils with a relatively high clay content.

b. In basic geotechnical literature, relatively little information is found on the subject.

Since one of the basic requirements with regard to a soil to be used as a liner is its relatively high clay content, and since such soils are called "cohesive" because of the presence of cohesion when undisturbed, it should be mentioned that most of the normally consolidated remolded soils lack such a cohesion (Seed et al, 1960). This observation was made with the consideration that any compaction operation is, to a certain degree, a remolding operation.

As Mitchell (1964) stated, "Perhaps the single most important reason for soil compaction is to increase the soil strength". It has been shown that CBR strength of a silty clay is directly related to the density achieved over a wide range of moisture contents. As has been shown (Mitchell, 1964), at water contents over the optimum, the CBR strength was also affected by the water content during compaction.

The strong dependence of the "as-compacted" CBR strength on density at moisture contents below the optimum moisture is evidence of minimal structural effects. In this range of moisture content, densification is not associated with a considerable deflocculation of the soil structure. Strength is a strongly correlated function of density.

The opposite happens in the wet-side-of-optimum range where it is observed that irrespective of the magnitude of the compactive effort, the strength is the same at a particular moisture content (Burmister, 1964). Slightly higher densities obtained with greater compactive efforts and an eventual increase in strength effect are offset by a more deflocculated (weaker) structure.

The method of compaction also has a very large effect on soil strength. Its effect is manifested mostly on the wet-side-of optimum (Seed and Chan, 1959; Seed et al., 1960). Whether a static or a kneading compaction procedure is used on the dry-side-of optimum, the characteristic structure of the soil will be the flocculated one and, at the same moisture content and density, the strength will be unaffected by the method of compaction. In the high range of moisture content, the kneading compaction is much more efficient in deflocculating the structure and, at the same density and moisture content, the soil is considerably weaker than the soil compacted statically. Seed et al. (1960) performed unconsolidated-undrained (UU) strength tests on a compacted silty clay soil and found that the statically compacted samples were four times as strong as those compacted by kneading. As Seed et al. made clear, only the general trends of the observed behavior can be considered as being valid; strength properties of soils can vary appreciably with regard to the compactive effort and the method of compaction.

The observation revealed by the work performed at the University of California, Berkeley (Mitchell, 1956; Mitchell, 1964; Seed and Chan 1959; Seed et al, 1960), that the strength of the statically compacted soil is greater than the strength of the soil compacted in a kneading device refers to values of shear stresses recorded at relatively small strains (5%). When values of shear stresses corresponding to larger strains (20%) were considered, no differences were found. The explanation advanced was that the prolonged shear in a statically compacted sample generated a structure similar to the one characteristic for the sample prepared by the kneading compaction procedure. This raises an important practical problem: in assessing the value of the shear stress for a particular design purpose, consideration has to be given to the range of meaningful strains. Since the strength determined is used to calculate slope stability, a safe procedure would be to consider the "ultimate" value of strength (Lambe and Whitman, 1979) or the "residual" one (Skempton, 1953), which means "shear stresses at large strains".

It is known that, at the same void ratio, the strength of a flocculated soil is larger than the strength of a dispersed one (Mitchell, 1956), which reiterates the fact that, in the case of many clay soils, the soil structure is of paramount importance. Often, the effect is so large that, if samples of the same soil subjected to different histories are brought to the same density and moisture content via soaking and consolidation or swelling, the stress-strain and strength properties will be still different because of the difference in the initially established structure (Mitchell, 1964). This structural difference will generate different patterns of pore-water pressure development with the result that, if the strength of these structurally different soils were to be assessed in terms of effective stresses, no difference in strength would be found between the two samples (Seed and Chan, 1959).

Pore-water pressure characteristics of a soil during shear are a reflection of clay structure which depends on the chemical and mineralogical characteristics of the clay. It has been proven that even a partial replacement of an exchangeable cation can substantially alter the strength of clays (Moum and Rosenquist, 1961). Since the waste effluent differs in chemical composition from the pore-water solution, cation exchange reactions can be anticipated which can have a substantial effect on strength and permeability properties of the soil.

While the strength of an "as-compacted" soil can be determined relatively easily, the strength of the in-place soil liner is harder to determine. Saturation, consolidation, or swell are some of the important changes which can operate in the field with important repercussions on stress-strain and strength properties (Seed et al, 1960). The relatively simplified situation in which the soil soaks under a certain confining pressure and then is loaded to cause deformation at constant volume is simulated in the laboratory by a consolidated undrained (CU) test; this is the usual procedure for assessing soil strength for pavement and earth dam designs. In this situation, the strength will be dependent on structural characteristics and void ratio since both determine pore-water pressure characteristics during shear. Samples of a silty clay soil, prepared by kneading compaction at different densities and moisture contents, if soaked with no change of volume, will be stronger with lower compacting moisture content if the stress at 5% strain is considered; at larger strains (20%), the strength is unaffected by the moisture content during compaction (Seed et al, 1960).

Regarding the stress-strain relationship and the way it relates to composition during compaction (density and moisture content), for structure-sensitive soils, the more flocculated the structure, the larger the shear-modulus, the stiffer the soil (Seed and Chan, 1959). In testing a silty clay soil in consolidated undrained compression (σ_3 = 2.0 kg cm^{-2}), it was shown that the lower the moisture content during compaction (the more flocculated the structure), the larger the deviator stress at any particular strain. Simultaneously, the pore-water pressure was higher with larger compaction moisture content so that the effective principal stress ratio or the effective obliquity index (σ'_1/σ'_3) was practically the same over a large range of moisture contents during compaction. This again emphasizes the functional relationship between chemical and mineralogical characteristics-structure-pore water pressure-strength (Mitchell, 1964, p. 89).

5.2.3 Designing of Soil and Clay Liners

As a hydraulic structure, a clay soil liner is designed with the main purpose of obtaining a blanket which will considerably impede the movement of the liquids waste into the adjacent, undisturbed soil. The clay soil candidate should be tested with the waste to determine the effect upon permeability. Soil strength considerations will not be looked upon in this section because of their secondary importance. If, for particular areas of the waste-disposal site soil strength characteristics are relevant (for instance, in conjunction with slope stability), the designer will recommend compaction procedures which will yield the required strength without detrimentally affecting the impermeability of the site.

Another facet of the design process for soil and clay liners is the provision for keeping adequate construction records and documentaiton, as well as retention of representative samples of field molded and compacted samples of liners and subgrade. The above records and samples will allow for timely and efficient verification of the construction and provide sufficient baseline data to evaluate ongoing performance.

The temporary immobilization of some contaminants along the depth of the soil liner is likewise not considered in this section, being probably negligible compared to the attenuation in the underlying soil often with a greater depth than the soil liner. Disregarding the attenuation capacity of the soil liner will produce an error on the safe side.

The starting point of the analysis for design should be the limiting seepage, the permissible flux q_p, between the soil liner and the underlying soil. This level of tolerable flux will be obtained as a result of a careful consideration of the following factors:

a. Waste-disposal site characteristics

- Size
- Shape and the angle between the long side of the waste disposal site and the direction of groundwater flow.

b. Waste-effluent characteristics

- Number of pollutants at a dangerously high concentration
- The concentration (c) of the pollutant for which there is the highest ratio c/d.w.s. (d.w.s. = drinking water standard)

c. The attenuation capacity of the underlying soil and its capacity to render groundwater contamination less probable.

d. Groundwater characteristics

- Depth
- Flow rate.

e. The sink-source distance, i.e. the distance between the contamination point (the waste-disposal site) and the usage point (the well depleting the aquifer).

Once the q_p value (the seepage between the soil-liner and the underlying soil) is obtained its value should be incorporated into the analysis to generate the soil permeability K for the known geometry characteristics and material properties of the system. A discussion of such an analysis is provided in Appendix VI.

As it has been indicated in previous sections on testing procedures, three main soil characteristics have to be investigated:

a. Soil compactibility

b. Soil flow properties

c. Soil chemical sensitivity.

Soil compactibility is determined by performing the Proctor compaction test. The results, the optimum moisture and particularly the maximum density, have to be judged by the designing engineer using background information on texturally similar soils.

Soil flow properties shall be determined on samples prepared using one of the indicated ASTM procedures. The fluid to be used, at this stage, is either tap water or 0.01 N $CaSO_4$ solution. The results of this test, coupled with the Proctor compaction data, will reveal the ranges of soil moisture content during compaction and soil densities where soil permeability drops below the required soil permeability corresponding to the permissible flux q_p. Comparing the two sets of data (soil compaction and soil permeability), the designer will be faced with the following situations:

a. There is a broad range of moisture content (w) and of soil bulk density (p) where the permeability (K) is less than the permissible permeability (K_p). Moreover, the two ranges practically overlap. This is expressed in Figure 5-4 by a unique relationship between p and K.

   This situation is the safest possible and the design engineer should not have any problems in optimizing the moisture of the soil during compaction and the corresponding density. If, in the tentative calculations, the depth of the soil liner D_e was on the high side (around 5 feet), the findings of the two tests reveal a way of reducing it. Such a reduction should not increase the flux q between the soil liner and underlying soil to more than 0.8 q_p.

b. There is a range of moisture content (w) over which $K<K_p$. The corresponding range of density is in absolute terms, on the low side. The soil achieved a state of low permeability not because of densification but rather because of shear deformation and particle orientation. Since it will be risky to rely on the stability in time

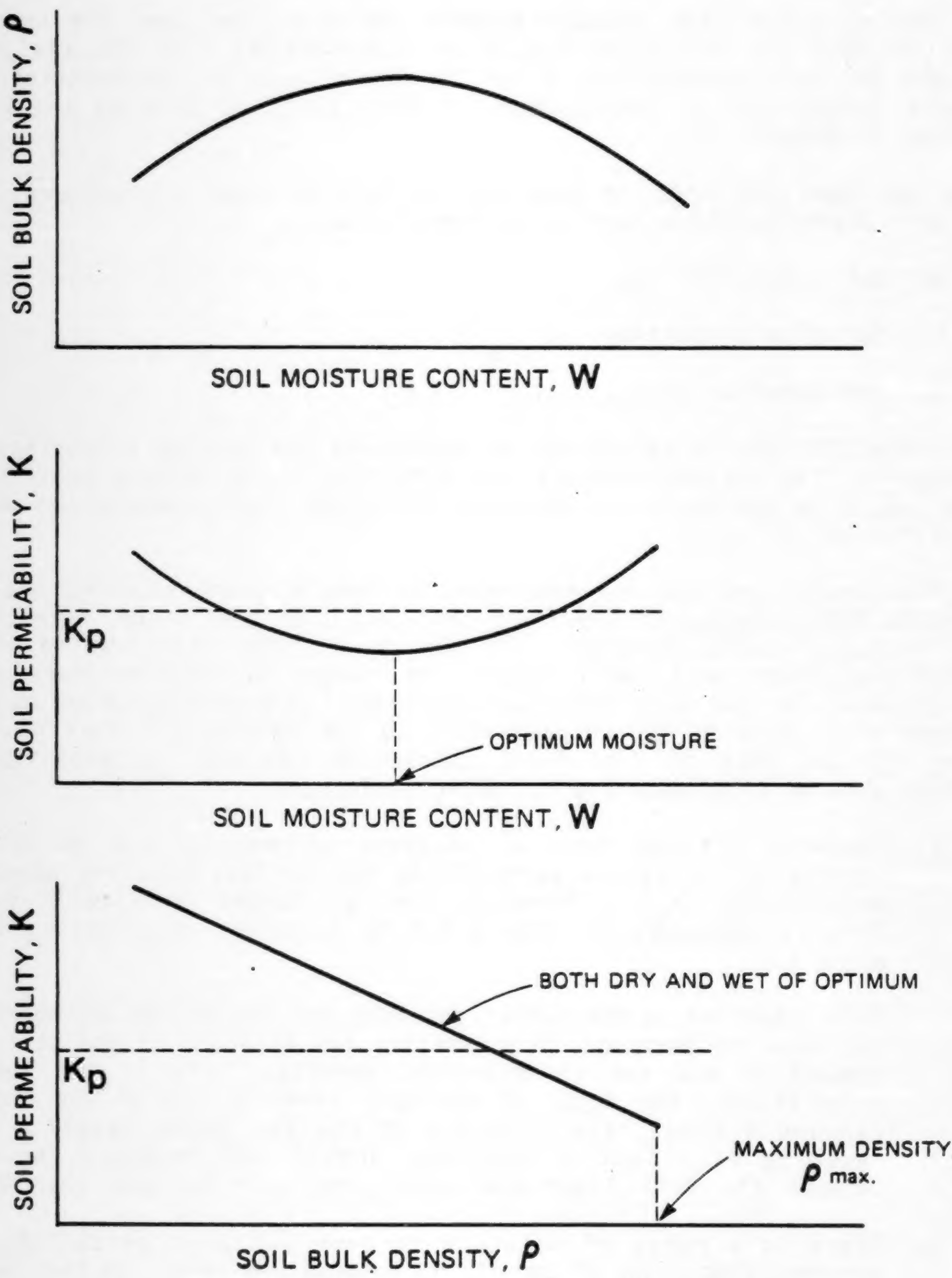

Figure 5-4. Schematic representation of the relationships w-ρ, w-K and ρ-K, for an idealized soil with no particle orientation when compacted at high moisture content. (Case 1).

of this structure, the soil must be compacted at a lower moisture content, a higher density, and a higher permeability. The designer has to readjust the depth of the soil liner D_e (increase it), such that the condition $q = 0.8\ q_p$ is still observed. The condition describing this situation is presented in Figure 5-5.

c. The required K_p value cannot be obtained. For this situation the only alternative, if economically feasible, is to increase the depth of the soil liner D_e and design for a larger K than originally planned. The import of a better soil material or fundamentally changing the type of lining, e.g. admixes, polymeric membranes, etc. should be considered at this stage.

The preceding discussion has to be considered only as a recommended procedure in using the test results for design. Often a more extensive research program is needed before the optimum design criteria are reached. Furthermore, it is to be expected that some recommendations generated at the end of the testing program cannot be easily translated into field compaction criteria for the preparation of the soil liner. The extrapolation of the test results for the field condition has to be done very carefully. The best approach is to understand the field condition and the construction limitations and perform the tests paralleling them as closely as possible, so that no extrapolation will be required.

5.2.4 Excavation and Embankment Construction

5.2.4.1 Excavation and sidewall

After planning and design stages are completed, construction activities commence. In most instances, the "earthwork" is performed by a general engineering/construction contractor. The types of equipment utilized vary with the size and complexity of the job. Small impoundments may require only tractors with dozer blades, water trucks and compactors, while large jobs may require additional vehicles including side loaders, graders, trucks, backhoes, front end loaders, trenching machines, and conveyor systems. (Figures 5-6, 5-7 and 5-8).

If surface water develops to a significant degree because groundwater is encountered during excavation, potential detrimental effects on the success of the subsequent liner installation may evolve. The presence of free standing water in the excavation will not only hinder the work of heavy equipment, but also will severely hamper liner installation activities. Similarly, rainfall can hinder excavation activities, and, in some cases halt work by creating adverse trafficability. If free water persists at the impoundment base, an artificial base may have to be constructed. Generally, gravels of various sizes are packed into the earth, then covered with sand or other available material such that a stable, firm working surface for later grading is achieved. Costs are greatly increased by the need to build a water-free surface for a liner installation in wetted areas.

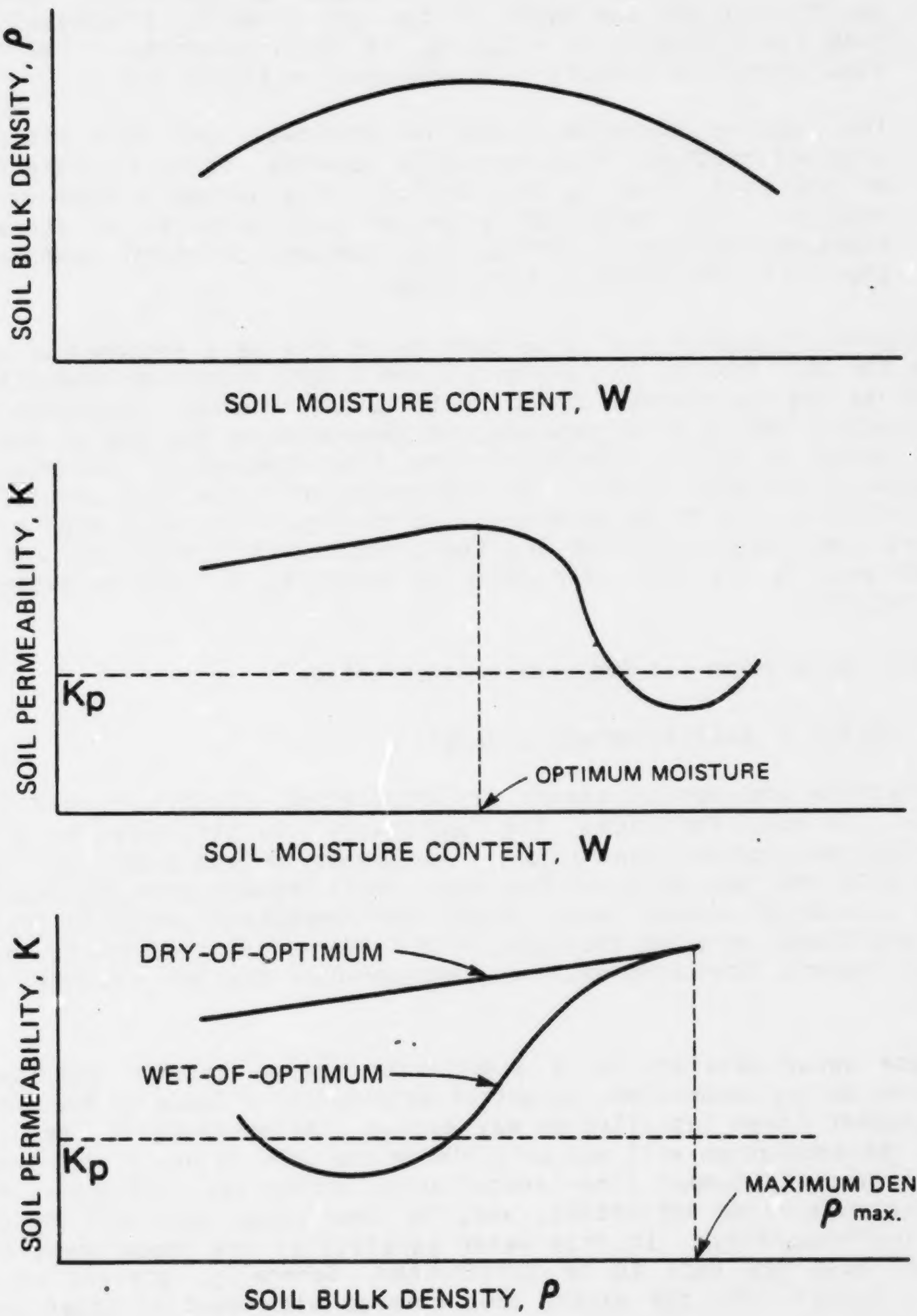

Figure 5-5. Schematic representation of the relationships w-ρ, w-K and ρ-K, for an idealized soil with no particle orientation when compacted at high moisture content. (Case 2).

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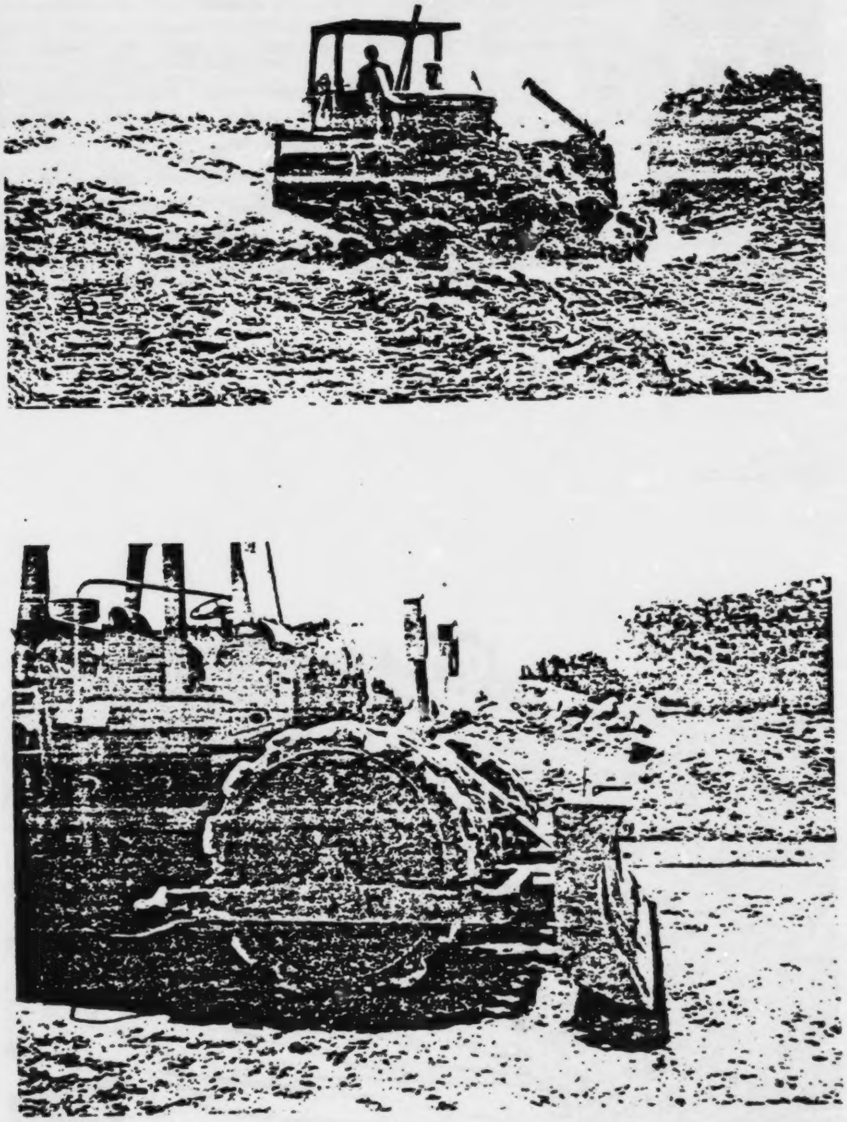

Figure 5-6. Typical earthwork equipment used during impoundment construction, dozer with blade (top) and dozer with compactor and blade (bottom).

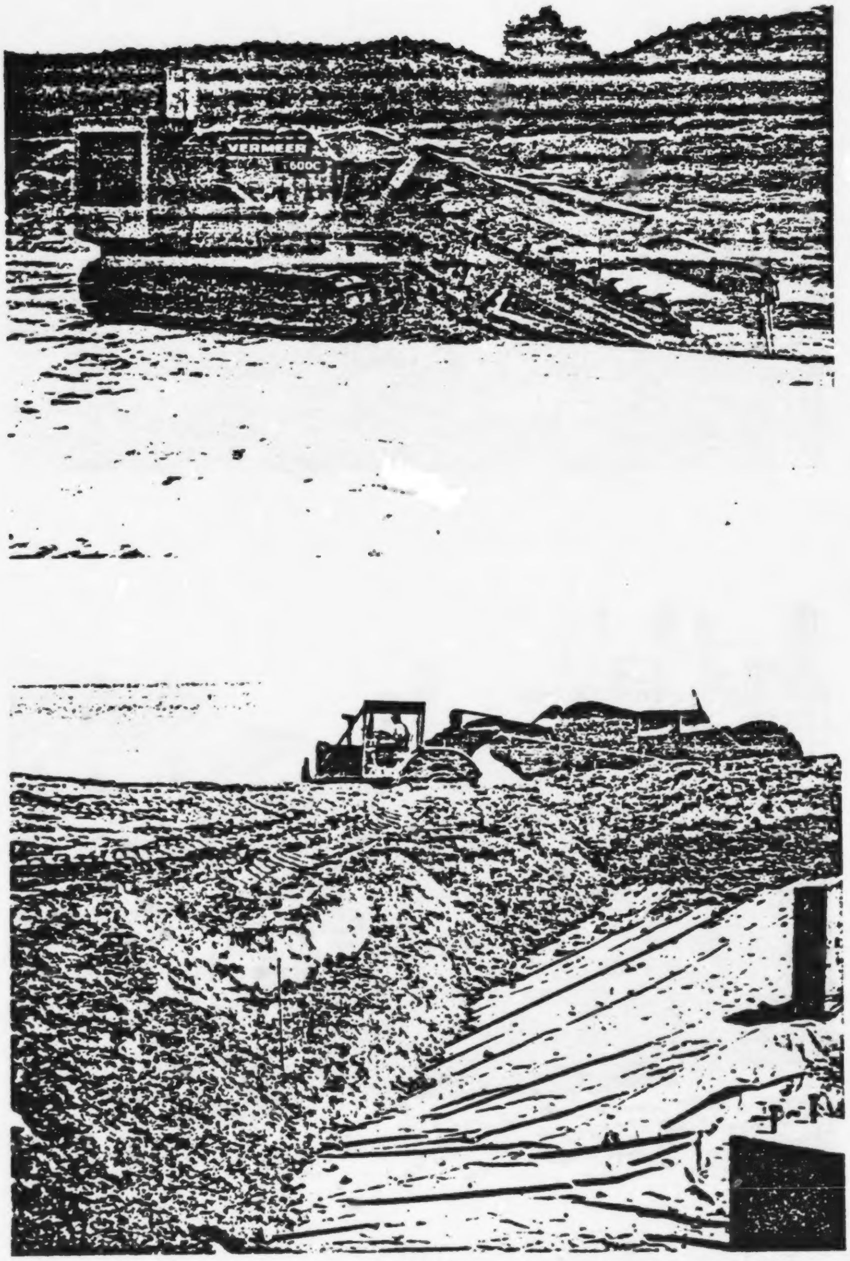
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Figure 5-7. Trenching machine for anchor trenches (top). Dozer and earth mover for berm construction (bottom).

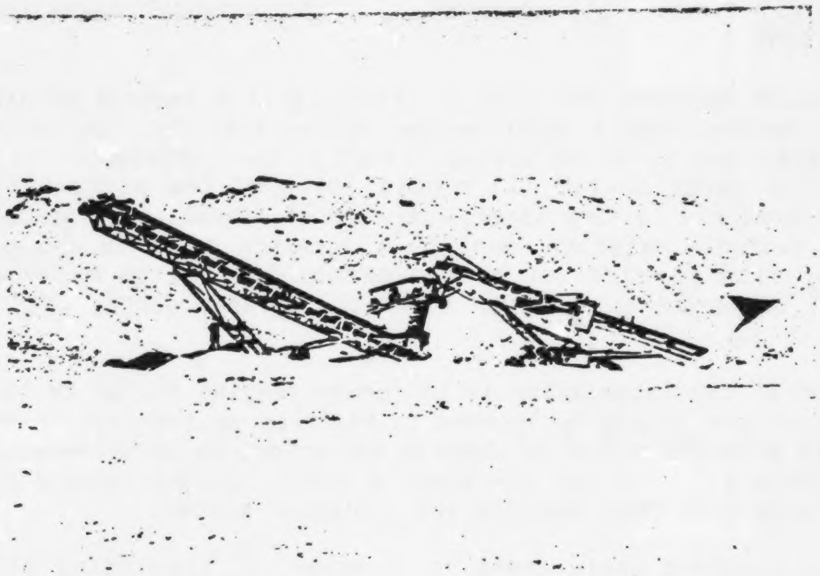

Figure 5-8. Conveyor system used during impoundment construction.

During the excavation process, all vegetation (tree trunks and roots in particular) should be removed from the site. Any depressions resulting from stump removal or similar condition should be filled in with suitable backfill.

Slopes will be constructed by normal techniques. Most construction equipment, including self-propelled compacting rollers, can be operated on slopes up to 3:1 during normal conditions. However, during periods of precipitation, even on 3:1 slopes, additional arrangements may be needed to ensure that equipment can travel safely up and down slope. A simple link to a large dozer, another heavy piece of equipment, or a winch stationed at the top of the sidewall/berm can be utilized. The equipment at the top then helps to pull the working unit up the slope, and helps to retard its downslope progress on the return trip.

When the side slope is steeper than 2:1 the "helping hand" approach is mandatory. One method is to chain two similar pieces of equipment together for cross slope work, such that the "helper" traverses the flattened top of the embankment while its chainlinked "twin" works the slanting side slope. Of course, extreme care must be observed during operations of this type. Road graders or vibrating rollers linked side-by-side by chain are an example of the type of equipment which might be used like this.

5.2.4.2 Drainage and leak detection/control systems

An underdrain system may be necessary where there is a high groundwater table or source of water infiltration. Underdrain systems may serve the purpose of transmitting fluids beneath and through the impoundment site without interaction with any contaminants from the impoundment facility. Kays (1977) identifies the following five parts in an underdrain system: (1) interceptor, (2) collector, (3) filter, (4) conveyor, and (5) disposal mechanism (See also Cedergren, 1967.)

The interceptor receives any liquids resulting from leakage or natural drainage. Interceptors should underlie the entire facility, including the sidewalls, if they are to be effective. Usually, the interceptor is composed of the following three parts: (1) a base layer of low permeability, (2) an overlying permeable lattice layer, composed of gravel, open graded asphalt or some other suitable material, and (3) a covering layer to protect the overlying liner from penetration by the permeable lattice materials; fabric materials (like geotextile filter blankets), graded earth, coarse sand, and others are in use.

The function of the interceptor is to convey seeping fluids to the collector. The collectors are generally located in blankets or trenches in the bottom of the facility with the number of feeding collectors being dependent on the size of the impoundment and the collector's basic design. Underdrain tile and perforated pipe have been used for the collector system.

Filters are required where there is a danger of the lining material fines (clay soil lining) working into the interceptor material. Filters can be constructed in the field of graded permeable soils, or may be one of the many commercial filter media now available. The purpose of the filter is to stop the migration of particles within the system. The movement of particles into the conveyance and collector can, and will, eventually inhibit the acceptable operation of the underdrain system. Any sign of turbidity in liquid issuing through the underdrain system could be a sign that the filtering system may be failing. According to Kays (1977), "The filter is an item often neglected in an underdrain complex. Its omission is responsible for triggering many malfunctions."

The underdrain monitoring system feeds into a closed pipe conveyance. The conveyance system must be sized to handle more than the expected optimal flows, as any backup within the system can cause serious repercussions (e.g. instability of the embankment). Kays (1977) advised that the conveyances terminate in sumps, channels, drains, or concrete exit structures.

The underdrain monitoring system should allow any leakage from the impoundment to be detected and managed. Some facilities have pumping arrangements whereby leakage and underflow are pumped and returned directly into the impoundment, while others collect the seepage and dispose of it offsite.

A critical need for an adequate drainage system will exist if groundwater is present immediately below the impoundment. A well designed underdrain system will minimize or eliminate (1) reverse hydrostatic pressure and (2) removal of soil from beneath the liner due to groundwater flow. Reverse hydrostatic pressure occurs when the groundwater level exceeds the operating water level in the impoundment. This could occur, for example, during normal level fluctuations in a drinking water reservoir. The groundwater reverse pressure can then push on the back side of the lining system, causing liner failure. Soil may be removed by groundwater flow below a liner, eventually causing the liner to rupture. If possible, sites where high groundwater exists should be avoided.

5.2.4.3 Monitoring wells

Facilites which store toxic/hazardous wastes will be required to monitor the condition of ground and surface water adjacent to the impoundment. Frequently, observation wells are drilled using normal techniques, standpipes inserted, and samples are taken and analyzed periodically. Most monitoring wells are pipes into which a water sampler can be lowered.

5.2.4.4 Field compaction of soil for construction of lined waste disposal facilities

The compaction of soil is an essential step in the construction of all types of liners, whether they be soils for a clay soil liner or for a subgrade on which admix, flexible membrane, or spray-on liners will be installed. Since the soil liner must have low permeability, emphasis in the compaction of soil for use as a liner is placed on achieving as low permeability as feasible. The requirement for strength is secondary, but it is needed for the embankments and dikes. For the subgrade, compaction of soil is needed to improve structural strength, uniformity of the subgrade, and smoothness. The subgrade sidewall particularly needs improved strength for stability. In this subsection, field compaction of the soil, the equipment, and the field tests required in the construction of lined waste disposal sites are described.

The applicability and requirements for the various pieces of compaction equipment that can be used to achieve desired compaction is presented in Table 5-3 taken from Coates and Yu (1977), pp. 90 - 91. The adequacy, use and efficiency of each piece of equipment varies with numerous factors including the following: (a) type, (b) weight and transmitted energy, (c) thickness of layers, (d) placement water content, and (e) material to be compacted.

The types of equipment in general use for gross compaction include sheepsfoot rollers, rubber tired rollers, smooth wheeled rollers, crawler tractors and tampers. Vibrating baseplate rollers, power tampers (or rammers) and manual tampers (or rammers) are used for fine finishing work both in the base and sidewalls. (See Figure 5-9). Power tampers and manual tampers are a necessity for backfill compaction of trenches or where penetrations of the base or sidewalls occur, e.g. around pipes, inflow/outflow/overflow structures and specialized supporting structures.

Compaction equipment can be selected based upon weight and transmitted energy requirements. For noncohesive materials, compaction can be adequately achieved with track type crawler tractor and/or haulage units as light pressure and vibration is the most effective methodology. Frequently, complete drying and rewetting is necessary to destroy the bulking effect of surface tension created by soil moisture. Very firm compaction can be achieved on sands, gravels, and rock fill by the use of heavy vibratory wheeled compactors.

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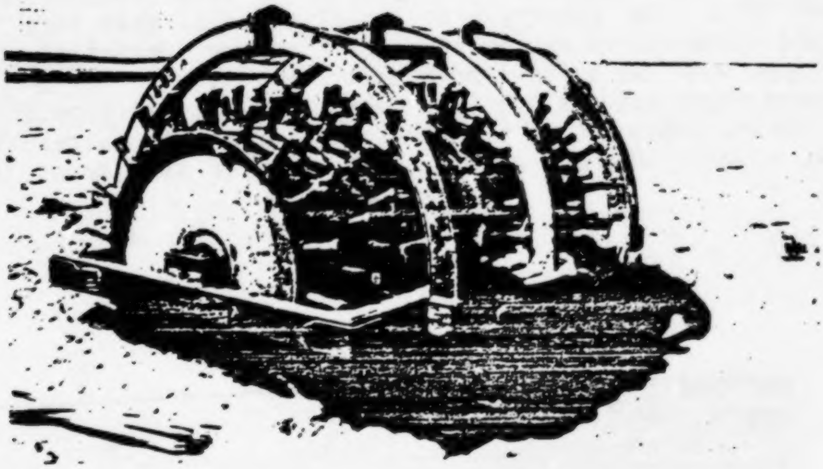
Table 5-3. COMPACTION EQUIPMENT AND METHODS[a]

<table>
<tr><th rowspan="2">Equipment type</th><th rowspan="2">Applicability</th><th colspan="3">Requirements for compaction of 95 to 100 per cent Standard Proctor, maximum density</th><th rowspan="2">Possible variations in equipment</th></tr>
<tr><th>Compacted lift thickness, in. (cm)</th><th>Passes or coverages</th><th>Dimensions and weight of equipment</th></tr>
<tr><td>Sheepsfoot rollers</td><td>For fine-grained soils or dirty coarse-grained soils with more than 20% passing No. 200 mesh; not suitable for clean coarse-grained soils; particularly appropriate for compaction of impervious zone for earth dam or linings where bonding of lifts is important.</td><td>6
(15)</td><td>4-6 passes for fine-grained soil;
6-8 passes for coarse-grained soil</td><td><table><tr><th>Soil type</th><th>Foot contact area, in.^{2} (cm^2)</th><th>Foot contact pressures, psi(MPa)</th></tr><tr><td>Fine-grained soil PI > 30</td><td>5 - 12
(32 - 77)</td><td>250 - 500
(17 - 34)</td></tr><tr><td>Fine-grained soil PI < 30</td><td>7 - 14
(45 - 90)</td><td>200 - 400
(1.4 - 2.8)</td></tr><tr><td>Coarse-grained soil</td><td>10 - 14
(64 - 90)</td><td>150 - 250
(1.0 - 1.7)</td></tr></table>Efficient compaction of wet soils requires less contact pressures than the same soils at lower moisture contents.</td><td>For earth dam, highway, and airfield work, drum of 60-in. dia. (152 cm), loaded to 1.5 - 3 tons per lineal ft (43.7 - 87.5 kN per lineal m) of drum generally is used; for smaller projects, 40-in. dia (101 cm) drum, loaded to 0.75 to 1.75 tons per lineal ft (21.9 - 43.7 kN per lineal m) of drum is used; foot contact pressure should be regulated so as to avoid shearing the soil on the third or fourth pass.</td></tr>
<tr><td rowspan="2">Rubber tire rollers</td><td>For clean, coarse-grained soils with 4 - 8% passing No. 200 mesh.</td><td>10
(25)</td><td>3 - 5</td><td rowspan="2">Tire inflation pressures of 60 to 80 psi (0.41 - 0.55 MPa) for clean granular material or base course and subgrade compaction; wheel load 18,000 - 25,000 lb (80 - 111 kN); tire inflation pressures in excess of 65 psi (0.45 MPa) for fine-grained soils of high plasticity; for uniform clean sands or silty fine sands, use large size tires with pressure of 40 to 50 psi (0.28 - 0.34 MPa).</td><td rowspan="2">Wide variety of rubber tire compaction equipment is available; for cohesive soils, light-wheel loads such as provided by wobble-wheel equipment, may be substituted for heavy-wheel load if lift thickness is decreased; for cohesionless soils, large-size tires are desirable to avoid shear and rutting.</td></tr>
<tr><td>For fine-grained soils or well graded, dirty coarse-grained soils with more than 8% passing No. 200 mesh.</td><td>6 - 8
(15 - 20)</td><td>4 - 6</td></tr>
<tr><td rowspan="2">Smooth wheel rollers</td><td>Appropriate for subgrade or base course compaction of well-graded sand-gravel mixtures.</td><td>8 - 12
(20 - 30)</td><td>4</td><td>Tandem type rollers for base course or subgrade compaction, 10 - 15 ton weight (89 - 133 kN), 300 - 500 lb per lineal in. (3.4 - 5.6 kN lineal cm) of width of real roller.</td><td rowspan="2">3-wheel rollers obtainable in wide range of sizes; 2-wheel tandem rollers are available in the range of 1 - 20 tons (8.9 - 178 kN) weight; 3-axle tandem rollers are generally used in the range of 10 to 20 tons (89 - 178 kN) weight; very heavy rollers are used for proof rolling of subgrade or base course.</td></tr>
<tr><td>May be used for fine-grained soils other than in earth dams; not suitable for clean well-graded sands or silty uniform sands.</td><td>6 - 8
(15 - 20)</td><td>6</td><td>3-wheel roller for compaction of fine-grained soil; weights from 5 - 6 tons (40 - 53 kN) for materials of low plasticity to 10 tons (89 kN) for materials of high plasticity.</td></tr>
<tr><td>Vibrating baseplate compactors</td><td>For coarse-grained soils with less than about 12% passing No. 200 mesh; best suited for materials with 4 - 8% passing No. 200 mesh, placed thoroughly wet.</td><td>8 - 10
(20 - 25)</td><td>3</td><td>Single pads or plates should weigh no less than 200 lb (0.89 kN); may be used in tandem where working space is available; for clean coarse-grained soil, vibration frequency should be no less than 1,600 cycles per minute.</td><td>Vibrating pads or plates are available, hand-propelled or self-propelled, single or in gangs, with width of coverage from 1.5 - 15 ft (0.45 - 4.57 m); various types of vibrating-drum equipment should be considered for compaction in large areas.</td></tr>
<tr><td>Crawler tractor</td><td>Best suited for coarse-grained soils with less than 4 - 8% passing No. 200 mesh, placed thoroughly wet.</td><td>10 - 12
(25 - 30)</td><td>3 - 4</td><td>No smaller than D8 tractor with blade, 34,500 lb (153 kN) weight, for high compaction.</td><td>Tractor weight up to 60,000 lb.</td></tr>
<tr><td>Power tamper or rammer</td><td>For difficult access, trench backfill; suitable for all inorganic soils.</td><td>4-6 in (10 - 15 cm) for silt or clay; 6 in. (15 cm) for coarse-graded soils</td><td></td><td>30 lb (0.13 kN) minimum weight; considerable range is tolerable, depending on materials and conditions.</td><td>Weights up to 250 lb (1.11 kN); foot diameter 4 to 10 in. (1.57 - 3.93 cm).</td></tr>
</table>

[a] Coates and Yu, 1977, pp. 90-91.



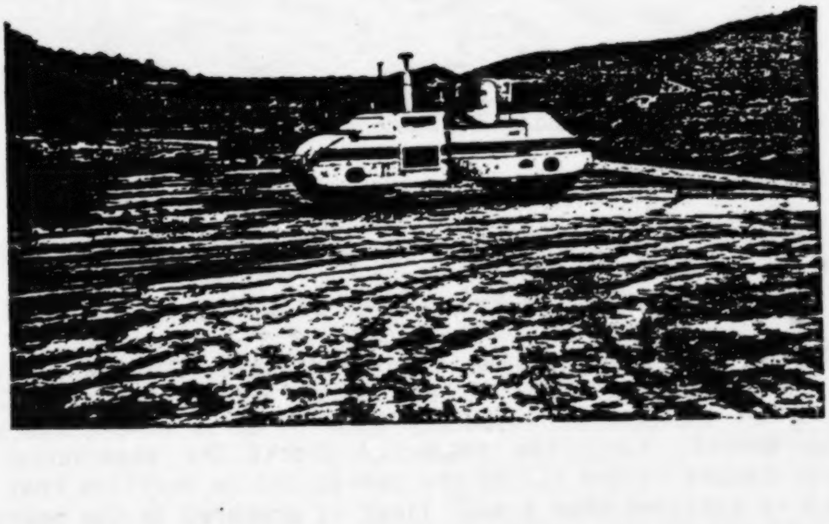


Figure 5-9. Typical compaction equipment.

Layers of cohesionless material up to 24 inches in thickness can be compacted with the vibratory rollers. Generally, stones in the cohesionless material should be no larger than two-thirds of the specified layer thickness (Coates and Yu, 1977).

Heavy sheepsfoot rollers, pneumatic rollers, and vibratory compactors are well suited for cohesive materials. The control of water content is essential in achievement of a high density with cohesive soils. When clay is the lining material and rubber-tired equipment is utilized for compaction, the surface of a given layer will be quite smooth after compaction. In certain instances where seepage might occur along this smooth plane, scarifying of the compacted layer to insure adhesion of the overlying layer will be necessary. Figure 5-10 shows a water vehicle used to add water to soil prior to compaction.

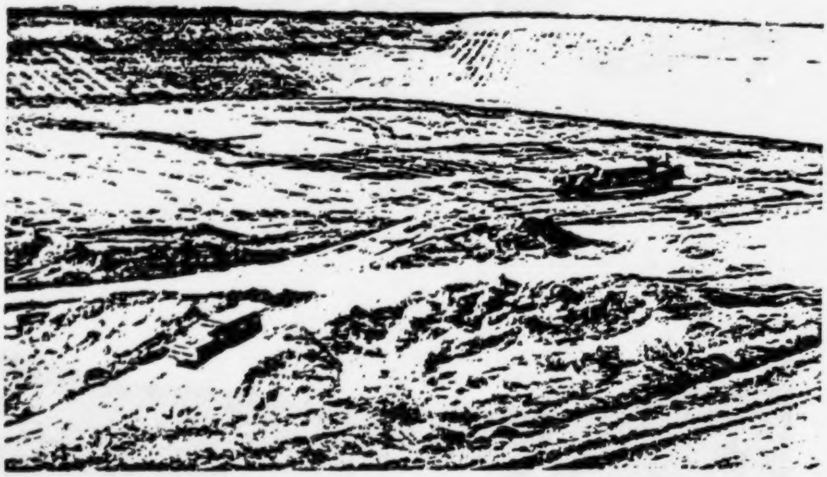


Figure 5-10. Water vehicle used to prepare the soil for compaction.

5.2.5 Quality Control in Preparation of a Clay Soil Liner

A soil blanket compacted to line a waste disposal impoundment should comply with the requirements stated in the design specifications. Compliance is monitored by an independent inspector both in terms of procedure and performance requirements, i.e., the inspector checks the observance of the construction procedure called for by the design and he verifies that the designed performance is achieved when a soil liner is prepared in the specified manner. These two objectives are met in the course of construction by visual inspection and by testing. At no time during the construction should visual inspection be the only form of quality control.

Inspection of the contractor's activity via sampling and testing should be established before construction begins. This sampling and testing program, followed on a regular basis, should provide the owner of the facility with a general picture of the quality of the construction work that is being performed. In addition to this quality control program, the inspector should visually inspect the constructed soil liner for areas which he suspects may not be meeting the design specifications. In such cases, the inspector should set up a specific testing program to determine the quality of those areas expediently.

One aspect of the inspector's task is to assess the quality of the construction in terms of its potential performance as a soil liner. Because of his continual presence in the field, the quality control inspector has the opportunity to spot unusual site conditions not detected during the preconstruction investigation and thus not singled out by the design specifications. In this situation, the design specifications may be found not to have been detailed enough. For example, although constructed in accordance with the specifications, the permeability of the soil could be found to be unusually high. If such a situation occurs, the inspector should see that the new information is immediately transmitted to both the designing and constructing parties and that steps are taken to adjust the particular design specifications and the corresponding construction procedures in light of the new information.

The procedural specifications which have to be observed by the contractor and assessed by the quality control inspector can be grouped in three categories: those which represent soil characteristics during compaction, those which are characteristics of the compacting implements (e.g. roller characteristics), and those which characterize the compaction operation itself. In the new few paragraphs, we indentify these characteristics.

1. Soil Characteristics

   a. Control of soil moisture content prior to and during the liner preparation (compaction).

      The moisture content of the soil should be in the ±1% of the designed w-value. Even if the density requirements are met at a lower value of w, the required moisture content has to be observed, because, for the purpose of generating a liner of low permeability, the moisture content during compaction is an essential factor, independent of its effect on density.

   b. Control of soil density.

      The inspection team has to assess the compliance of the compaction operation using the Field Density Test Procedure Designation E-24 (Bur. Rec., 1974) and the Rapid Compaction Control Test Procedure Designation E-25 (Bur. Rec., 1974). For the **clayey and silty soils, the minimum field density should be 95% of the Proctor maximum density of the fraction smaller than 4.75 mm (#4 sieve).**

If the results of the density tests are only marginally acceptable, the contractor should be asked to improve the compaction operation. In this case, the inspector should determine if the increase in density due to the undertaken improvement of soil compaction is accomplished by a decrease in permeability; thus, the inspector must assess the efficiency of the newly recommended densification procedure. The uniformity of soil compaction, both horizontally and vertically, should be verified and observed.

2. Roller characteristics

The contractor should observe the design specifications referring to:

a. Size, arrangement, and safety features of the drums.

b. Number, location, length, and cross-sectional area of the tamping feet.

c. Weight of the loaded roller. (As a general rule, the weight should be over 4,000 pounds per foot of length of drum.)

3. Characteristics of the Compaction Operation

The design requirements should be rigorously followed with regards to the following:

a. Number of passes.

b. Thickness of layers. (The first lift should always be compacted with extreme care and it should not be more than 8" loose lift.)

c. Thickness of layers in relation to length of tamping feet. (Each compacted lift should be less than 2/3 the length of the tamping feet so that the roller can ride high over the compacted lift and insure bonding of successive layers.)

The extent of sampling and testing for moisture content and soil density cannot and should not be rigidly stated. This is because, in some circumstances, the compaction operation may increase the heterogeneity of a field site, and in others decrease it. Let us consider, for instance, a hypothetical situation in which a limited area is isolated in the design specification as being covered by a "uniform" soil, i.e. a soil unit which, prior to and following the compaction, is considered "uniform" in terms of density, moisture content, and flow characteristics. Assume further that this area is not as uniform as it was originally thought and that 10% of it is covered by a soil unit which reacted quite differently to the recommended compaction procedure. As a consequence, there is a possibility that, following liner preparation, the heterogeneity of relevant characteristics will be increased in comparison to the uncompacted soil.

When the soil is "uniform" to start with and when a unique compaction procedure is followed in the field, the soil should become even more uniform following compaction. Thus, for example, assume that 30 density determinations were done to characterize a soil prior to compaction, that the average value was determined to be 90 lb/ft^3, and that the normally distributed values around this average were spread between 86 and 94 lb/ft^3, with a standard deviation equal to 1.95 lb/ft^3. Following compaction, the same hypothetical area was again sampled and the average density value of the 30 determinations was (as was designed) equal to 110 lb/ft^3. The two extreme values were 108 and 112 lb/ft^3 with a standard deviation equal to only 0.95 lb/ft^3. This indicates that 95% of the field was compacted at a density range between 108.1 and 111.9 lb/ft^3. Thus, theoretically 2.5% of the prepared soil liner was compacted at densities smaller than 108.1 lb/ft^3 and 47.5% at densities between 108.1 and the required value of 110 lb/ft^3. If, as we previously indicated, this designed value represents 95% of the maximum Proctor density, the value of 108.1 lbs/ft^3 corresponds to 93.4% of the maximum Proctor, i.e. 2.5% of the soil will be compacted at densities lower than 93.4% of this maximum. Tentatively, we estimate that this value is an acceptable one and any value of 90-92% of the maximum for at most 2.5% of the soil should be considered as reflecting a uniformly dense soil liner.

The significance of the results of moisture content and soil density determinations is questionable in relation to quality control, however, if these results are not related to the density/permeability relationship. Knowledge of this relationship will allow the designer to perform simple calculations such as those presented in the previous paragraphs, and to assess how much undercompaction can be tolerated safely. Briefly, if a soil's permeability is not significantly higher at 90% of the maximum Proctor in comparison to its permeability at 95%, a relatively large spread of density values can be considered acceptable. In this case, if 2.5% of the soil is compacted at densities less than 90% of maximum, undercompaction is an admissible alternative. However, if the permeability increases drastically when the soil is undercompacted, the required standard deviation of the density values should be minimal, i.e. 2.5% compacted to less than 93-94% of maximum Proctor is not acceptable.

The most significant requirement for a soil liner underlying a waste disposal site is its low permeability. To assess the permeability, the inspector should perform both laboratory testing and field trials. The inspector should verify that the K-value is within the required range, and he should also correlate the permeability with the density-moisture content function, thus verifying the relationships obtained during the pre-construction investigation, upon which the whole design is based. If, over a certain limited area, the relationships seem to be different from those obtained in the preliminary investigation, the designing group should be informed immediately and asked to assess the magnitude of the effect in terms of additional discharge below the liner. If this additional flux is judged to be unacceptable, new requirements should be given to the constructing group. The inspector should then assess the efficiency of the revised compaction procedures as observed by the contractor.

As we already indicated above, the sampling and testing procedures in the quality control program should be established before construction begins so that they are available to the inspecting unit. To give an example of the extent of an "adequate" quality control program, given the construction of a hypothetical soil liner, three feet in depth, that is to cover an area equal to 100 acres, the following number of samples may be required:

a. For determining the moisture content prior to compaction, and the density obtained following the compaction, one soil sample for every 2,000 cubic yards of compacted soil liner.

b. For determining the laboratory saturated hydraulic conductivity, one soil sample for every 16,000 cubic yards of compacted soil liner.

c. For monitoring the field infilterability, one determination for every 40,000 cubic yards of compacted soil liner.

These densities for sampling and testing will result (for the hypothetical waste disposal facility) in determining the moisture content and density of 242 samples, in performing 30 laboratory permeability determinations, and in performing 12 infiltration tests in the field.

The above example should only serve to give a very general idea of adequate densities for sampling and testing. For instance, a liner designed at a depth of 24 inches or less should be sampled and tested at a higher density. In a real situation, local conditions may dictate a degree of bias in comparison with the present example. Some of the circumstances which will allow the inspection team to use a different sampling procedure are likely to be the following:

a. The soil cover has an unusually low or unusually high degree of homogeneity.

b. The degree of detail and accuracy of the preconstruction investigation is unusually low or unusually high.

c. The soil to be compacted is unusually homogeneous and or unusually heterogeneous in terms of its initial moisture content.

The duration of the construction period and the extent of precipitation during the course of construction should also be considered. The magnitude of the area to be lined should not be a factor in establishing the density of testing. Every unit area of the waste disposal site should be controlled with the same care, regardless of the size of the site to be lined.

Apart from the general program of sampling and testing related to a unit volume of compacted earth, there should be occasional samplings, particularly in the first stages of the construction operation and often as a result of visual observation. These samplings will mostly likely be prompted by the following conditions:

a. A systematic increase in the thickness of a lift over the specified value.

b. A moisture content of the uncompacted soil out of the specified range.

c. A reduction in the required number of passes.

d. A "different behavior" under the roller of a particular area.

Sometimes, specifications may require the construction of a test area on the site prior to the construction of the liner itself. If this is the case, and if the outcome of compaction and moisture control are satisfactory, most of the testing during the construction of the liner may be limited to that of samples collected per unit volume of compacted soil liner. Density and permeability tests in such a construction test area would provide valuable information for use in determining the quality control strategy.

Often, a laboratory will need to be organized as close as possible to the future waste disposal site. The particular type of facility needed depends on the amount of earthwork involved (i.e. the number of samples to be tested), the types of tests to be performed, the expected testing load per unit time, the duration of the operation, etc. Detailed information on this subject can be found in the Earth Manual (Bureau of Reclamation, 1974).

A detailed report on the control work performed should be maintained daily. These reports are useful in tracing whatever work was not performed according to the specifications.

In the last 25 years, several radiation techniques have been developed for determining both moisture content and soil density. However, only in the last decade has substantial progress been made in the use of neutron thermalization techniques for determining moisture content or in gamma rays and neutron attenuation for determining both moisture content and soil density.

The radiation methods are potentially useful for work performed during the quality control activity. Some of the quoted advantages of these techniques are their nondestructive nature, their ability to sample a relatively large specimen, and their ability to be performed quickly. Among the disadvantages are the fact that a careful calibration is required prior to testing for every soil unit and that only a limited resolution is obtainable (i.e. soil discontinuities are not sharply detected). However, these procedures have to be better adapted for use in relation to liner construction.

The laboratory saturated permeability should be determined using Designation E-13 (Bureau of Reclamation, 1974; ASTM D-2434-68, 1974), or a falling head technique (Black, 1965).

A field procedure for the determination of soils infilterability that can be confidently applied in the case of soil liners is not really available. However, the ASTM D-3385-75 or Designation E-19 in the Earth Manual can be used. It should be indicated that, particularly with regard to the field determination of water transmission characteristics of a soil liner, the available methods should be improved and new procedures developed for measuring waste transmission.

b. A moisture content of the uncompacted soil out of the specified range.

c. A reduction in the required number of passes.

d. A "different behavior" under the roller of a particular area.

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5.3 Construction of Linings of Admixed Materials

5.3.1 Introduction

Admixes refer to a variety of formed-in-place materials such as soil cement, concrete, asphalt concrete, and bentonites. The characteristics of these are described in Chapter 3, Section 3.3. The field construction of these lining materials is discussed in the following subsections.

5.3.2 Soil Cement

Soil cement liners can be made from standard or plastic soil cement mixes. The latter contains more cement and water than the former. Best results are obtained when the cement is mixed with a well graded sandy soil (maximum size 3/4 in) as the cement is the minor ingredient. Type V sulfate-resistant cement is recommended when the soil contains sulfate as determined by laboratory tests. The design mix should be tested by the moisture-density relations test ASTM D558, wet-dry test ASTM D559, freeze-thaw test ASTM D560, and the permeability tests of E-13 in the Bureau of Reclamation Earth Manual.

Soil cement is placed using road paving methods and equipment, but it should not be placed when air temperatures are below 45°F. The compacted density should be 98% of the laboratory maximum density. The compaction should proceed so that no more than one hour elapses between the spreading and compacting of a layer. Several stages of the installation of a soil cement liner are shown in Figure 5-11. The surface of a compacted layer must be kept moist by fog spraying if another layer is to be applied. The finished liner should be allowed to cure for seven days. Soil cement must be sealed. The sealing compounds are bituminous liquids and emulsions sprayed onto the soil cement surface after it has been sprayed with water to reach its maximum water absorption level. This spraying should be done as soon after compaction as practical (Day, 1970).

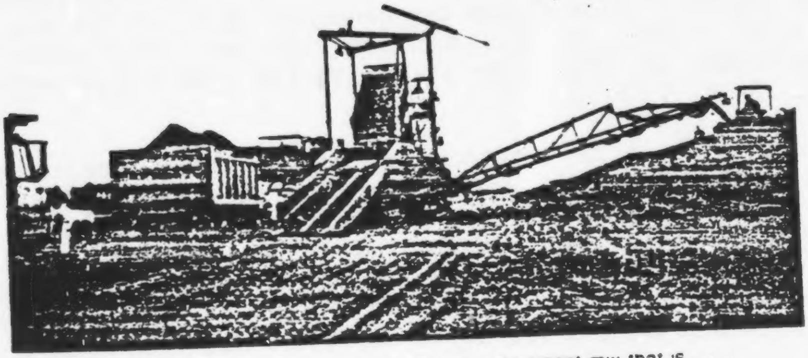
5.3.3 Concrete and Cement

The details of procedures for construction, subgrade preparation, placing and curing of cement concrete liners may be obtained from the Bureau of Reclamation's Concrete Manual 1975, and from consulting engineers in this field. However, some considerations and procedures are presented below.

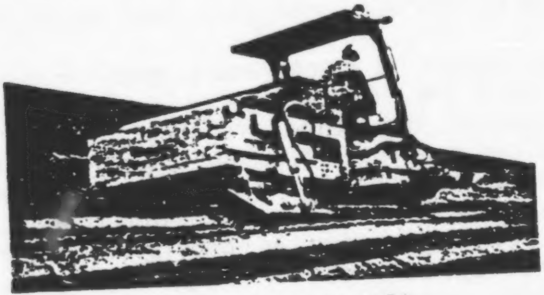
Subgrade preparation is particularly important if there is a possibility of high hydraulic pressures against the liner. A layer of gravel or drainage system should be placed beneath the liner. The subgrade should be well moistened just before placing the concrete. This will help prevent the liner from drying too quickly (Bureau of Reclamation, 1963).

Concrete mixes for pond liners should be plastic enough to consolidate well but stiff enough not to slip on side slopes. A concrete mix with a slump of 2 to 2.5 inches is usually satisfactory. It is important to control carefully the workability and consistency of the concrete; a change of one inch in slump will interfere with the quality and progress of the work. The maximum recommended size of aggregate is 3/4 inch or less for a liner 2-1/2 inches thick.

Placing machine is custom built to handle 10,000 cu yd of soil-cement a day.



Conveyor boom extends 100-ft to dump soil-cement mix that is . . .



compacted by rollers in stepped lifts of 9-in.

Figure 5-11. Steps in the installation of a soil-cement liner (Brown and Root, Inc., 1978).

The inclusion of air entraining agents is strongly recommended in areas where the liner will be exposed to freezing temperatures (Bureau of Reclamation, 1975).

The actual placing of the concrete may be done by slip form or the use of a screed. Finishing of liners is not necessary since it is of little useful value in this type of situation. Curing is important. The use of accepted sealing compounds is recommended to produce satisfactory results.

Shotcrete or gunite is cement mixed with sand of maximum size of 3/16 inches, although 3/4 inch aggregate is used for some structural shotcrete. The relatively dry mix is "shot" through a large flexible hose by pneumatic pressure. Moist curing or use of a curing compound is necessary for shotcrete. Gunite may be used as a liner by itself but generally requires an asphaltic or membrane seal to attain the required permeability (Bureau of Reclamation, 1963).

5.3.4 Asphalt Concrete

Asphalt concrete for hydraulic structures such as a pond or landfill is similar to paving asphalt concrete but contains higher percentages of mineral filler and asphalt. Side slopes are generally 2:1. As the mix is not subject to automotive traffic it does not need the very high stability of paving asphalt concrete but should be stable on the side slopes when hot (Asphalt Institute, MS-12, 1976).

The subgrade should be smoothed by rollers after compacting the top six inches to at least 95% of maximum density by ASTM D1557. Initially, the subgrade is treated with soil sterilant to prevent weed growth. A prime coat of hot liquid asphalt is then applied to the surface and allowed to cure before paving. The hot asphalt concrete mix should be placed by spreaders equipped with hoppers and strike-off plates or screeds. They should be capable of producing courses 10 to 15 feet wide, free from grooves, depressions, holes, etc. Ironing screeds used with strike offs and screeds on the spreader should be heated to at least 250°F before starting operations to prevent sticking or tearing of the surface. Placing should be planned to minimize the number of cold joints. Figure 5-12 shows the placing of a two-inch thick asphalt concrete liner with road paving equipment.

The edges of spreads should be smooth and sloped for 6 to 12 inches to provide a bonding surface with the adjacent spread. Cold sufaces should be heated with an infra-red heater just before forming joints. Asphalt concrete mixtures should be applied to slopes from bottom to top (Day, 1970). Generally, best results are obtained when the side slopes are paved before the floor (Asphalt Institute, MS-12, 1976). The asphalt concrete liner should be compacted as soon after spreading as possible. Ironing screeds, rollers, vibrators or tampers may be used for compaction (Day, 1970). In order to achieve a permeability coefficient of less than 1×10^{-7} cm s^{-1}, a voids content of 4% or less is required (Asphalt Institute, MS-12, 1976). When a liner thickness greater than 3 inches is required, multiple courses should be applied. All joints should be staggered to insure strength and low permeability for the liner as a whole (Day, 1970, pp. 56-59).

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best available copy.

Figure 5-12. A two-inch thick asphalt concrete liner is applied using road paving equipment and methods. After the surface cools, a seal coat is applied (Shultz, 1982).

5.3.5 Construction of Bentonite-Clay Liners

Several methods are available for the preparation of a lining based upon fine grain commercially processed bentonite. Such a bentonite can be used as a 1 to 2 inch thick membrane covered with 8 to 12 inches of earth or gravel (to protect the clay liner from erosion or mechanical damage) or it may be mixed in with the soil to form a uniform surface layer. The application rate for the latter is about one lb/ft^2 of soil. Similarly bentonite may be mixed with sand, in a volume ratio of approximately 1 to 8 (3 lb/ft^2 bentonite), spread in a layer 2 to 4 inches thick and covered. Bulk spreading and mixing of bentonite into a soil which has an unacceptable permeability is shown in Figures 5-13 and 5-13a. After thorough mixing, the resultant mixture is wetted and compacted (Schultz, 1982).

A slurry of bentonite (bentonite 0.5% by weight) may be added to existing (filled) ponds to decrease the permeability of the soil or gravel liner. The bentonite settles filling void spaces and effectively sealing the surface.

Bentonites vary in quality. The moisture content of the clay should be less than 20% especially for thin membranes. Wyoming-type bentonite which is finer than No. 30 sieve or well graded if coarser particles are present have proven very satisfactory (Middlebrooks et al., 1978).

For some uses, e.g. canals, bentonite slurry can only be a temporary seal. It is subject to shrinkage, cracking, and erosion from moving water. Also, any calcium in the water will cause an exchange with the sodium on the bentonite and an increase in permeability (Bureau of Reclamation, 1963).

5.4 Design and Construction of Flexible Membrane Liner Installations

5.4.1 Introduction

The purpose of this section is to discuss the factors pertaining to the design of systems for waste disposal facilities and to describe the methods and equipment used to line the waste disposal facilities with flexible membrane liner materials. Schultz and Miklas (1980) conducted a study to identify current methods and equipment used to (1) prepare subgrades for liners, and (2) place liners, particularly membrane liners. Much of the contents of this section and Appendix IV is based upon the results and observations of that project.

Flexible liner installations generally have similar planning, design and construction components. One of the most important components and one which is common to all flexible liner systems, is the subgrade, which serves as the supporting structure for these liners. The quality and integrity of the subgrade must be assured if the liner is to perform satisfactorily. Inadequate subgrade support accounts for many of the failures of liner installations.

Equally critical to a good project is the proper installation of the selected liner material over the subgrade. Installation involves numerous steps and

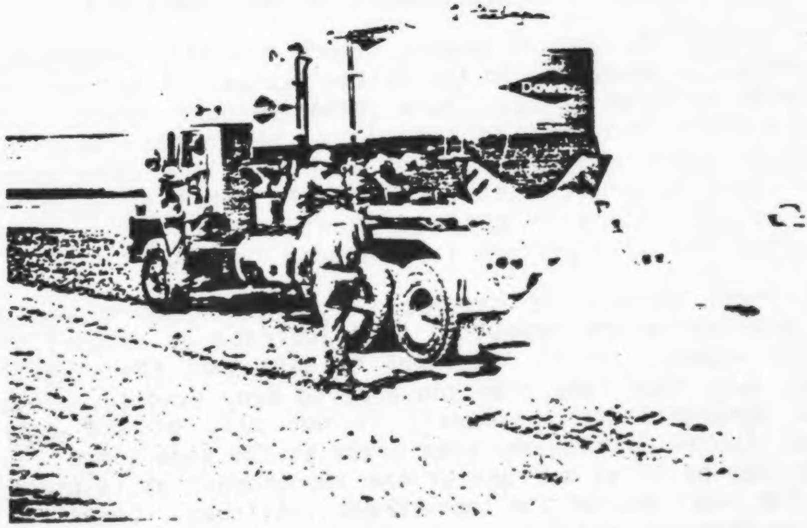

Figure 5-13. Bulk application of bentonite with an oil field bottle truck fitted with a six-foot wide distributor attached to the rear of the truck. An outrigger on the side of the truck allowed the operator immediate and safe access to the material control valves.

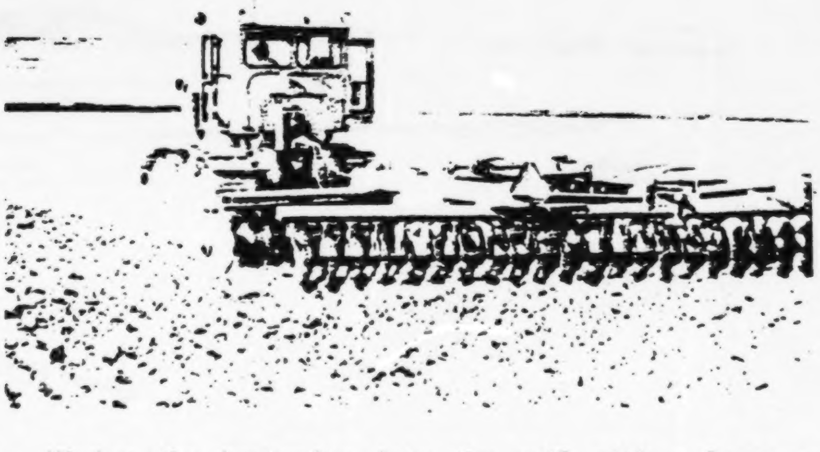

Figure 5-13a. Mixing the bentonite into the soil with a large agricultural disc. Eight passes on a crisscross pattern are made to mix in the bentonite. A large rototiller is also found to be useful in blending in the bentonite. Water is added to the soil-bentonite mixture which is then compacted.

planning before the job is begun. There are many experienced installers of liners presently operating in the United States. A partial list of installers is presented in Appendix II. These companies have personnel trained in proper field placement and seaming techniques which have been acquired through installation experience and contact with the liner fabricators and manufacturers. Such experience is needed by the owner of a facility and assures adequate compliance with project plans and specifications to produce an installation that will perform its intended function.

Each of these aspects is discussed in the following sections. Pictures, figures and tables are presented to illustrate or support the discussion of each major aspect. It is important to note that the size of lined impoundments can vary from less than one acre to many hundred. Because of the time and cost considerations, several, if not all, of the constructions steps discussed in this section may take place at the same time. For example, liner placement may be in at one end of the impoundment while the subgrade preparation at the other end of the impoundment continues. Landfills may be lined in modules or phases, making sure the lining is adequately protected during the time between lining installation and waste placement.

5.4.2 Planning and Design Considerations for Membrane Liners

Overall design and planning considerations for lining waste disposal facilities are presented and discussed in Section 5.1. In this section considerations which pertain specifically to flexible membrane liners are discussed in greater detail.

5.4.2.1 Type and texture of "in situ" soils

In the planning/site selection process, care should be taken to select the best available location for the proposed facility. The classification, relative homogeneity, and relevant physical, mechanical, and chemical character of the "in situ" soils should be determined. Consideration should be given to having the soils tested for Atterberg limits and grain size relative to "shrink/swell" moisture, density, strength, settlement, permeability, organic material content, clay mineralogy, ion exchange capacity, and solubility. Appropriate soils engineering test methods should be used.

Soils which have high "shrink/swell" characteristics should generally be avoided. The normal changes in soils which experience clay expansion (wet) and contraction (dry) may act to weaken an earthen structure, both at the bottom and on the sidewalls/berm structures, if the clay is allowed to be alternately wet and dry. Unwanted voids may be generated by repeated "shrink/ swell" cycles, introducing water into the structure, thus encouraging failure.

The presence of organic material in a soil below a membrane liner can cause a variety of problems. Organic material can generate gases through natural decay processes, and tree trunks and extensive root systems can create voids beneath the liner. If gases are generated beneath a liner, they may collect to the extent that the liner is pushed upward from the subgrade. The phenomena of membrane liner displacement by gases produces the undesired "whale back" effect where large portions of liner rise up and out of the liquid to be contained (like a balloon), eventually rupturing or requiring rupture to release the trapped gases. The decay of organic material can also create voids which lead to base material slumping, subsequent liner shifting and potential liner failure.

The soluble material in the foundation material beneath a liner can also cause both the gas and void problems. Any acid leakage, however minimal, which could reach a carbonate rich soil, might produce quantities of gas resulting in a catastrophic liner failure. The dissolution of the carbonate might also cause cavities and loss of liner support.

Removal of organic material and the installation of gas vents would be necessary if the soil contains organic material, or if other gas problems are known. The bottom of the impoundment must be sloped upward 2 - 4% minimum to allow gas to reach gas vents.

5.4.2.2 Subgrade characteristics

The liner subgrade must provide a relatively firm and unyielding support for the liner material. In this sense, the subgrade includes all excavated soil, all engineered fill and all trench backfill. The performance of the subgrade is dependent upon: (1) the loading it is subjected to by the weight of waste applied; (2) the subgrade characteristics and subsequent groundwater changes; (3) slope instability; (4) liner malfunctions; or (5) seismic activity. The main characteristics or relevance for subgrade materials are settlement (stress-strain relationship), consolidation (strain-time relationship), strength, and acid solubility. These parameters are readily determinable by field and laboratory tests. Simpler, less expensive tests which have been previously correlated with these tests are performed during construction to allow a thorough coverage of the subgrade quality. These simpler tests include Atterberg limits, grain size, and compaction tests. Strength and occasionally consolidation tests may be run on the subgrade earthwork, if deemed necessary by the quality control programs.

5.4.2.3 Desired characteristics of bottom and side surfaces

In most liner installations, the more plane and regular the subgrade side slopes and base are, the easier and more reliable will be the liner installation. The largest particles in the subgrade soil on which the liner is to be placed should be less than three-quarters inch with the fine finished subgrade surface having only smooth rounded particles less than one quarter inch in diameter exposed. Large gravel, cobbles, and boulders are to be avoided. Furthermore, the largest particles should be rounded to subrounded rather than angular. Where large particles are present, plan on either removing them by hand raking or grading at least 3 inches to 6 inches below the desired bottom elevation, and subsequently backfill with material with the desired particle size characteristics, compacting the added material to provide the desired homogeneous base and sides which are free from large particles. In case where subgrade roughness cannot be avoided, a suitable geotextile underlay, e.g. filter fabric, should be considered.

5.4.2.4 Location of bedrock

Carefully consider the alternatives to construction of a lined impoundment when rock removal (through blasting and other procedures) and rock shaping is required. The economic consideration will probably be paramount here, as the cost of working in rock is many times larger than construction activity in weathered rock or loose material. In addition, the potential for large angular particles and irregular surfaces is much greater. It may be desirable under such circumstance to construct a filled impoundment (see Section 5.1.1).

5.4.2.5 Stability of materials

The importance of utilizing a material with stable characteristics under differing loading and climatic/meteorologic conditions cannot be overemphasized. The reaction of a given soil to changes in stress or moisture content should be considered in the design of a given structure. The selection of side slope angles will also be governed by the ability of a selected material to maintain the selected grades. Generally, a 3:1 or less slope is safe for most materials, although seismic considerations may require flatter slopes. Wave erosion may cause sloughing of the cover soil within the operating liquid level and freeboard zone. This zone should be provided with erosion protection. Experience with earth dam design has provided us with a good source of practical design solutions for this problem (Bureau of Reclamation, 1973).

5.4.2.6 Drainage consideration

Surface runoff will be affected by the impoundment. If the impoundment is in the pathway of natural drainage, the diversion drainage systems, overflow structures and later subterranean diversion systems must be planned to handle the water excesses in order to minimize potential damage to the impoundment structure and minimize other adverse impacts. An underdrain system may be required to remove groundwater which accumulates beneath the installed liner through time. Infiltrating water beneath liners/impoundments is particularly common in areas with high subsurface flow, or high groundwater table; the problem must be recognized in advance so that design accommodations can be made if the integrity of the impoundment/liner is to be maintained throughout its projected life. Areas subject to flooding and areas with high water tables must receive special design, construction, operations and maintenance concern.

5.4.2.7 Impoundment dimensions

The most economical shape for an impoundment is rectangular with straight sides. Curved sides and irregular shapes usually add to the grading and installation costs and increase the number of structural failure points that can occur. Avoid circular impoundments as the grading costs and installation costs for liner materials will be increased significantly along with the construction costs.

5.4.2.8 Wind direction and velocity

Design of the pond must take into consideration the prevailing winds. Winds adversely affect the liner in two principal ways, in the form of wave action as the wind impinges on the liner and in the form of lifting action on the slopes in the case of membrane liners. Proper venting of the membrane liner at the top of the slope can mitigate or negate the airfoil effect created by the slope. The placement of weight tubes on the slopes also helps to break up the flow of air across the pond in addition to providing ballast to hold the liner on the slope (Small, 1980).

5.4.2.9 Ambient temperature

The temperature characteristics of the environment can be a factor in the liner selection process. Of particular significance are temperature extremes and the duration of those extremes. Materials that exhibit superior low temperature resitance to cracking may not be able to withstand the effects of high tempertures. Low temperatures along with strong winds can result in a flex fatigue type failure. Materials that creep at high temperatures may elongate to failure during cycles of high temperature (Small, 1980).

Low temperatures which can cause icing or freezing introduce another set of adverse factors to the structural integrity of the liner. Because of freeze-thaw cycling, the integrity of the subgrade may also be affected.

5.4.2.10 Local vegetation

In addition to gas problems, vegetation can jeopardize liner integrity as a result of growth. Certain grasses can penetrate flexible membrane liners. Use of thicker sheeting may reduce such damage. Where certain woody vegetation or grasses are evident, soil sterilization with an appropriate herbicide may be required to prevent damage to the liner. Salt grass, nut grass, and quackgrass are examples of local vegetation which mandate soil sterilization. The topsoil layer containing this vegetation should be removed as a part of subgrade preparation. If these grasses are present, soil sterilization should also be automatically included in the construction process. If a soil sterilant is used, polymeric liners should not be placed immediately after application. Time should be allowed for the sterilant to be absorbed by the soil or to lose its volatile components so that it will not react with the liner.

5.4.2.11 Floor consideration

The floor of the impoundment should not be flat if there is the possibility of gas production beneath the liner. The floor should be designed to slope upward with a minumum grade of 2% from a low point near the center in order to encourage gas movement out from beneath the liner. Since the vent design must provide a permeable material to relieve the gas to the atmosphere, it may also serve as a subdrain. The designer should provide for liquid gathering and release as well as for safe discharge of the vent gases. If the liner is being installed in a landfill in order to capture leachate, a leachate collection system may be required in order to manage the leachate as it forms and to allow the removal of quantities of infiltration water which may enter the landfill after periods of precipitation or snowmelt. Outside grades should be designed to prevent an influx of runoff water into the pond. Cut-off trenches should be used in mountainous areas to prevent washouts.

5.4.2.12 Berm width requirements

The width of the containment embankments will be determined by their height and the design side slope; the width of the berm is an optional design factor. The minimum suggested top width is ten feet in order to allow sufficient room for equipment and men to operate during liner installation, to provide room such that anchor trenches can be efficiently installed should they be required, and to facilitate maintenance and repairs throughout facility life.

5.4.2.13 Inflow/outflow/overflow conveyances

The fewer penetrations in a lined impoundment, the greater its probable integrity; thus, if possible, inflow/outflow piping should be designed to go "over the top". If inflow/outflow piping is required, select pipes made of materials which are compatible with the liner type. During installation, soil around the pipes should be well compacted to insure that voids and loose structures are eliminated. If an "over the top" inflow pipe is used, a splash pad may be needed to prevent system damage to the liner.

5.4.2.14 Monitoring and leak detection systems

If monitoring wells are needed, locate them both up gradient and down gradient of the impoundment so that the background quality can be compared with the possibly contaminated groundwater. The down gradient monitoring wells should be designed to monitor groundwater before the groundwater leaves the site facility boundary or emerges into a surface water body. The number of wells is dependent on the size of impoundment, the material stored, the relative need for early discovery of leaking material, and the environmental sensitivity of the local system (EPA, 1977).

Some hazardous substances to be stored in lined impoundments are potentially so damaging that the regulatory agency may require a leak detection system be installed immediately beneath the impoundment. The system will usually involve two liners; an underliner of clay or other suitable material will be overlain with one to three feet of permeable material. The underliner will slope toward a center low spot either at a point or along a trench which extends the length of the impoundment. A suitable liner material will be placed over the permeable material. If the primary (uppermost) liner leaks, the leaking material will be channelled to a collection point either via the trough or in the centralized low point. The leaking material will be collected, removed, and discarded either back into the reservoir or by other acceptable means.

Such a procedure as described above can indicate whether there is one or more leaks in a landfill or an impoundment, but gives no indication as to the location of the leak or leaks. It is highly desirable to know the locations of all leaks. For example, the time delay between the start of a leak and the pollutant entering the monitoring system can be lengthy. Also, if repairs can be made, the location must be known. To fill this need, EPA has undertaken research projects to investigate the feasibility of locating leaks and of developing leak detection techniques which can be applied to landfills. The initial study has indicated that developing such methods is feasible (Earth-Tech, 1982). Two contracts, 68-03-3030 and 68-03-3033, are ongoing to develop techniques for detecting leaks in old landfills and designs for leak detection systems which can be incorporated in new disposal facilities.

5.4.2.15 Monitoring liner performance

An important output of the planning and design process is a procedure to monitor the performance of the installed liner. The procedure should be relatively simple to perform and produce verifiable results (probably through coupon testing and evaluation and periodic groundwater monitoring). Ideally, the monitoring of liner performance should be in situ, nondestructive, and nondisruptive. Realistically, performance monitoring will most likely involve sampling of soils and waters from selected locations beneath the liner and/or the subgrade. This topic is highly site specific, and as such the factors and procedures differ for each facility.

The setting up of a "coupon" testing program is suggested in which samples of membrane from the same lot as the emplaced liner are placed in the waste at the start of operation of the impoundment and withdrawn and tested on a planned schedule. Such a procedure can be used for monitoring the condition of the actual liner during its exposure to the waste. The planning and design process must detail the coupon program. A more comprehensive treatment of this subject is presented in subsection 5.4.7.

5.4.3 Preparation of Subgrade for Flexible Membrane Liners

5.4.3.1 Compaction of subgrade

Compaction of the subgrade soil is required to provide a firm and unyielding base for most lining materials, be they admix, synthetic membrane, soil, or other. Generally, a fill subgrade is built up in a series of compacted layers, whereas an excavated subgrade is compacted only at its surface. Usually, the minimum compaction of the subgrade material will be specified. Most liner installations require the density of the subgrade achieve at least a specified percentage of that obtainable by the Standard Proctor Test, ASTM D698, with 90% of Proctor being the most specified relative compaction. Some contracts will specify the compaction equipment which is to be utilized, number of equipment coverages per layer, layer thickness, permissible water content range at placement,and method and location of water addition.

The regularity and texture of the surface of the uppermost layer in the compaction scheme is critical in the liner installation process. A plane surface after compaction is the most desirable one for liner placement but is not always achievable or specified in the contract. In many installations, soil clods or local surface irregularities will be flattened (further compacted) by the overlying weight of the stored material after the impoundment is filled. Further, it is thought that the flexible membrane liners will adjust their shape over any clods so that no detrimental effects will result. Nevertheless, rocks or irregularities with sharp edges should be eliminated from the finished subgrade during the compaction/ construction process even when not specified in the contract if a thin flexible liner integrity is to be maintained.

Within the flexible liner industry, there is a difference of opinion as to how smooth surfaces must be to insure liner integrity. The opinions vary with the liner material. All installers would agree, however, that the smoother the finished surface, the easier the task of flexible liner installation.

5.4.3.2 Fine finishing of surface

After compaction has been completed, it is normal to fine finish the surface. Fine finishing is an intensive aspect of subgrade preparation. Depending on the design specifications, various techniques are used. Often, teams of men (generally from two to ten depending on the size of the job) are assigned to scour the surface on both the base and sidewalls, looking for and removing rocks or debris. Men are also encouraged to tamp down any soil which can be manually disaggregated and spread.

The desirability of a smooth surface on the bottom and sidewalls has given impetus to the utilization of various drags to aid in the formation of a regular, flat working surface. Usually, the fine finishing with vibrating rollers and drags will need to be accomplished on a slightly wet surface; thus, water tank trucks are a familiar sight during the fine finishing activities. Fine finishing with a smooth steel roller is sometimes required. Occasionally, soil additions are required to bridge surface irregularities if the irregularities cannot otherwise be removed. Sand is useful for this purpose as it is easily compacted.

Figure 5-14 shows examples of subgrade that require additional work before a membrane liner can be placed. Figure 5-15 shows scraper and roller being used to fine finish a subgrade. Figure 5-16 presents examples of suitable subgrade texture prior to placement of a flexible liner.

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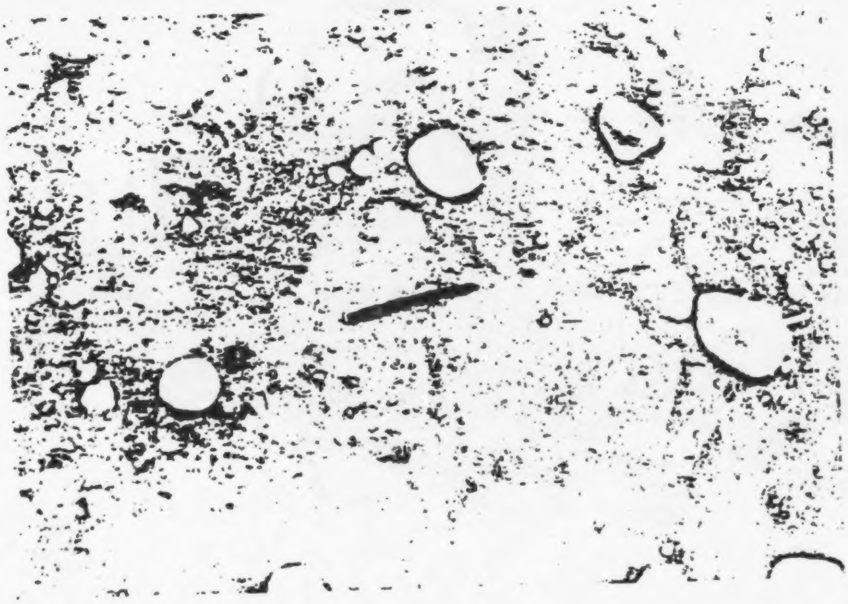

Figure 5-14. Photographs showing various stages of subgrade finishing. These subgrades require further work.

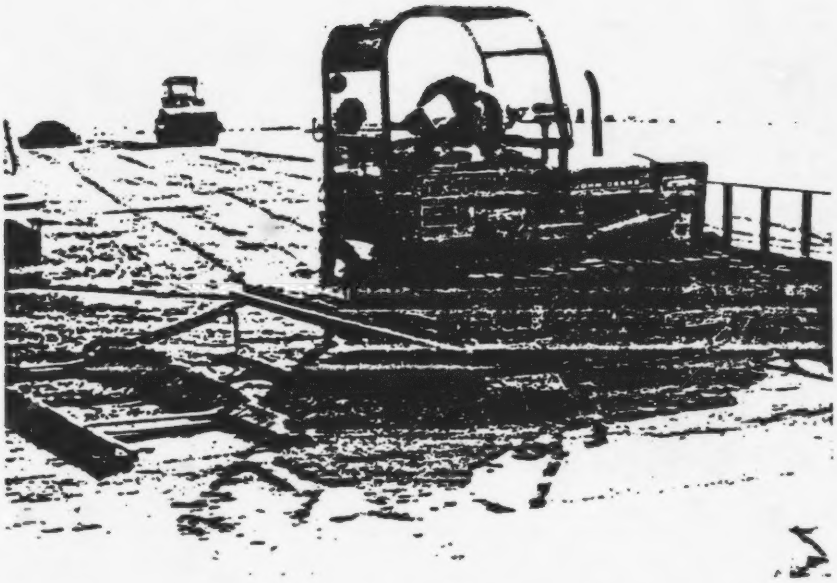

Figure 5-15. Scraper and roller being used to fine finish a subgrade

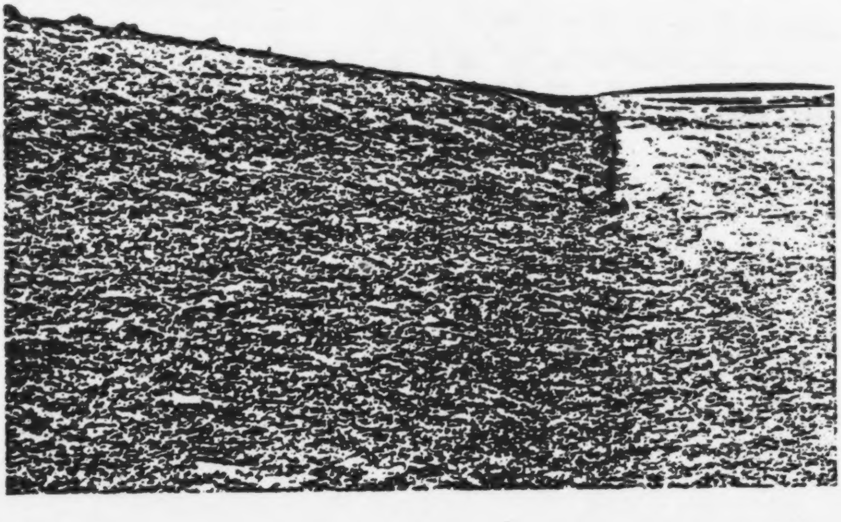

Figure 5-16. Representative subgrade surface texture prior to placement of a flexible liner.

The control of unwanted grasses and other types of vegetation is accomplished in the fine finishing stage through removal of the layer containing the vegetation and/or the application of a herbicide to the finished slopes and base. The selection of a proper herbicide is critical as some species found in western states are not killed by certain herbicides commonly used in the more humid eastern United States. All fill obtained off-site should be inspected well to ensure that both germinating and inactive seeds and roots are killed by the application of herbicide.

Generally, it is advisable to wait a few days before laying liner material. Figure 5-17 shows what can happen if a herbicide is not applied properly. The picture shows salt grass penetrating a 30 mil membrane liner. When applying herbicides, proper protection against inhalation and skin contact should be taken.

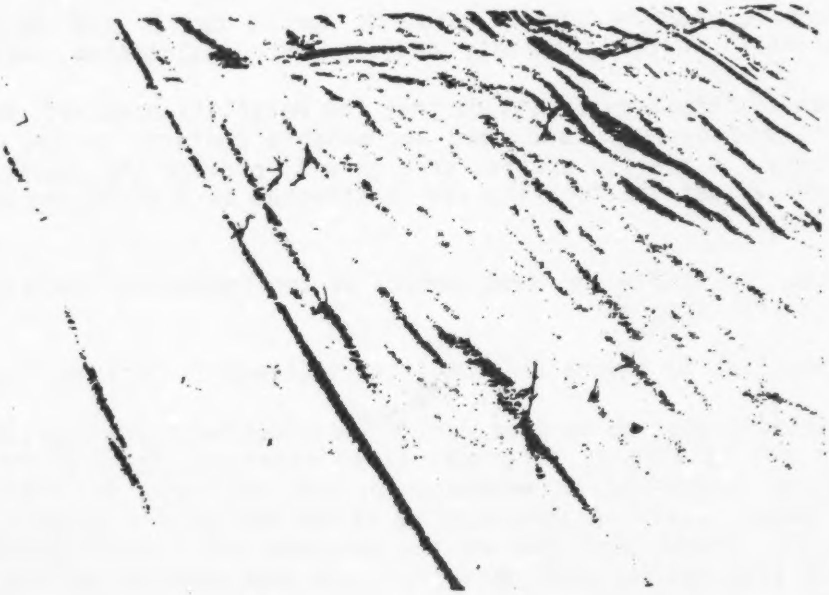

Figure 5-17. Salt grass penetrating a 30 mil flexible liner. Soil sterilization is important prior to placing a liner.

The activities of excavation, construction, trenching, compaction, fine finishing, and liner installation are generally all progressing at the same time on larger jobs. It is desirable during dry weather to apply water or other dust control compounds since the field seaming process is best completed in a dust-free environment.

The fine finishing process is critically dependent on the proper care and control of water. If rain occurs during or immediately after the fine finishing work on a slope, rills, ruts, ravines, etc. may be eroded into the surface. Thus, the expenditure of effort to fine finish slopes and bottom for subsequent membrane liner placement should be curtailed when rainfall is imminent; conversely, the placement of liner material on fine finished slopes should be as soon after completion of "finishing" as possible to ensure that no surfaces are "lost" to the erosive effects of surface runoff.

5.4.4 Liner Placement

The installation of flexible membrane liners requires a significant planning effort prior to construction. This planning effort must include consideration of the storage and security of all necessary equipment, installation equipment, manpower requirements, the placement operation, field seaming, anchoring and sealing, quality control, inspection, and protection of placed liners. All of these considerations are discussed in detail in Appendix IV.

5.4.5 Quality Control in Construction of Liner System

A comprehensive quality control program during design and construction is a vital element in the planning, design, and construction, and operation.

This program is necessary to assure that the materials used will meet facility requirements and demands, and that workmanship conforms to the installation specifications. A quality control program will provide the operator and owner with confidence that the facility was constructed as planned and will function as intended.

As a minimum, the following items should be considered for incorporation into a quality control program:

- A checklist to assure all facility requirements have been met.
- A specific plan to be used during construction for observation, inspection and testing of subgrade, liner material, factory and field seam quality, installation workmanship, and assurance that the design is followed. Daily records must be maintained of all aspects of the work and all tests performed on the subgrade and liner. For example, air lance seam testing with periodic field seam tensile testing.
- Throughout construction, a qualified auditor responsible to the operator/owner should review and monitor output. This is an ongoing check on the contractor/installer. It generates confidence that the work was indeed done as planned. Changes to planned procedures must be justified immediately and subsequently documented. This can avoid serious conflicts between the owner and design/installation team after the job is completed.

Quality control/inspection programs can result in more effective impoundments by assuring planned review and tracking of all activities comprising the facility design and construction.

There are three major specific areas of quality control concern in a polymer membrane lined impoundment. They are the subgrade, membrane seams, and sealing of penetrations through the liner.

A representative of the primary facility operator, or representative of the ultimate owner of a lined facility, is usually assigned as the quality control agent or engineer on liner installations. The agent will be required to assure that the contractural obligations of the installing contractor(s) are met and that the installation specifications are fully met. Personnel reviewing the design or performing quality control functions for a liner installation should be familiar with the liner manufacturer's recommendations regarding all facets of the material's use and installation. This includes everything from the liner's compatibility with the waste being stored to recommendations regarding specific adhesive systems and special seaming instructions around penetrations.

5.4.5.1 Subgrade

A quality control plan for the earthwork portion of the project serves two important functions. First, a uniform density is attained which assures both owner and engineer that the project is constructed as designed. Second, it provides the data necessary to control costs when field densities are higher than required: this eliminates the possibility of an increased volume of earthwork (Small, 1980). A quality control program should specify the test frequency to ensure accurate and reliable field density data and be tailored to the specific needs and requirements of the project. The factors to consider in establishing a quality control program for earthwork include, but are not limited to, the following:

1. Total project area.
2. Range of fill heights:
3. Number of soil types to be compacted.
4. Consistency of each soil type.
5. Haul distance.
6. Anticipated weather conditions.
7. Method of placement.
8. Method of compaction.
9. Geometry of the site.

It is a generally accepted practice to test each lift of soil placed. The number of tests per lift may very from one to ten tests per 20,000 square feet, depending upon the criteria developed for the project. Soil samples are normally taken and tested to ascertain that the subgrade materials are of the specified classifications and constituency. Measurements of moisture and relative compaction are periodically determined to ensure that the subgrade has the desired firmness. Visual observations of subgrade appearance, earthwork activities and workmanship, lack of vegetation, drain orientation and placement, curb and control of water as necessary, slope characteristics and preparation, and other parameters are conducted on an 'as needed' basis. In some instances, the original design of an impoundment must be modified in the field to accommodate unexpected conditions and unforeseen occurrences. Since membrane liner installations are new to many "earthwork" contractors, advice is often solicited from onsite personnel of the liner installer, fabricator, and/or manufacturer as unforeseen problems arise.

5.4.5.2 Flexible polymeric membrane liner

The success or failure of the liner installation will depend to a great extent upon the installing contractor's seam credibility. Job site factors which may influence the field seaming operation include:

1. The ambient temperature at which the seams are produced.
2. The relative humidity.
3. The amount of wind.
4. The effect that clouds have on the liner temperature.
5. The moisture content of the subsurface beneath the liner.
6. The supporting surface on which the seam is bonded.
7. The skill of the seaming crew.
8. The quality and consistency of the adhesive.
9. The cleanliness of the seam interface, i.e. the amount of airborne dust and debris present.

Seaming methods differ between liner materials. Cured materials or vulcanized materials such as EPDM and neoprene are usually sealed with a tongue and groove type seam using gum tape or a two part system. Uncured or unvulcanized material such as CSPE, CPE, and PVC are sealed using solvent, bodied solvent adhesives, or heat. Contact adhesive systems may also be used, however they do not develop the same seam strength as bodied solvent systems. Several pictures of field seaming are presented in Appendix IV. A new seaming method of fusion welding is shown in Figure 5-18.

Once the seam has been completed, it should be allowed to stand long enough to develop full strength. The three basic requirements for credible seam production by thermal methods are heat, pressure, and dwell time. In the case of an adhesive system, the adhesive takes the place of the heat. However, sufficient pressure and dwell time must be applied to create permanent bonding of the seam interface. An air lance test using 50 psi air directed through a 3/16" nozzle, held no more than 6" from the seam edge may be used to detect any holidays, tunnels, or fishmouths in the seam area. Testing the integrity of a seam with a "vacuum box" such as is used to test steel welds is shown in Figure 5-19 and an ultra-sonic method is also shown. Any imperfections should be repaired as soon as practicable. Once testing has been completed any exposed scrim (in the case of reinforced material) is to be flood coated with the same bodied solvent adhesive. The entire impoundment should be inspected to insure that all the field and factory seams are properly joined, no scrim is exposed and any damage which may have occurred during installation has been repaired. All patches should have rounded corners with the scrim properly flood coated to insure encapsulation.

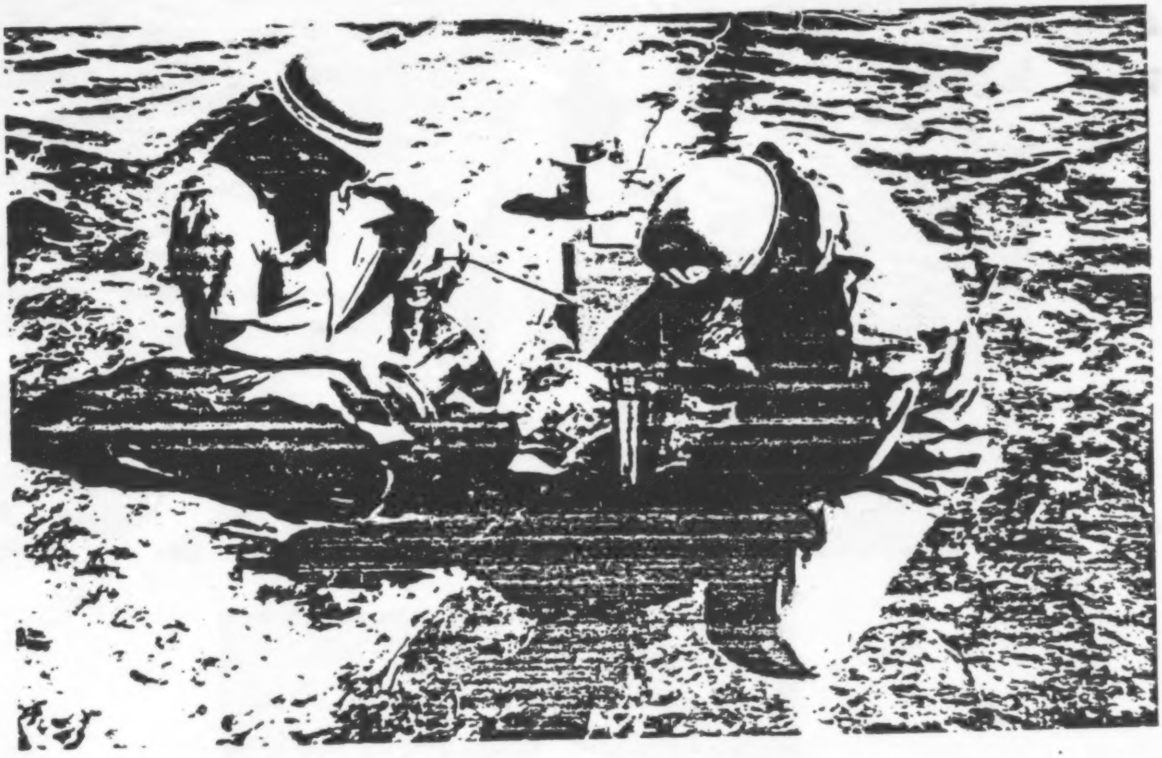

Figure 5-18. Seaming of HDPE liner with a fusion welder. (Courtesy of Gundle Lining Systems.)

5.4.5.3 Penetrations

Penetrations of a membrane liner, e.g. inlets and outlets, are a significant concern with respect to adequate sealing between the liner and the penetration. Where the penetration is round, stainless steel bands may be used. Screw-type clamps are well suited for small penetrations four inches in diameter or less. For larger pipes, "band-it" type methods may be specified. An extra layer of liner material should be placed between the band and the liner to prevent cutting or abrasion. Flange-type connections offer the most secure type of seal between the liner and pipe penetrations. Flanges should be set in concrete with anchor blocks tack welded to the back of the flange. Care must be taken to insure that the concrete is smooth finished with rounded edges. Additional layers of the liner may be placed over the flange extending to the full edge of the concrete so as to form a gasket and also to prevent abrasion between the concrete and the liner. Once the liner is placed over the flange, an additional layer should be placed on top to form the other half of the gasket seal (Small, 1980).

5.4.6. Earth Covers for Flexible Membrane Liners

Earth covers are commonly placed on polymeric, spray-on, and other membrane liners for two principal reasons:

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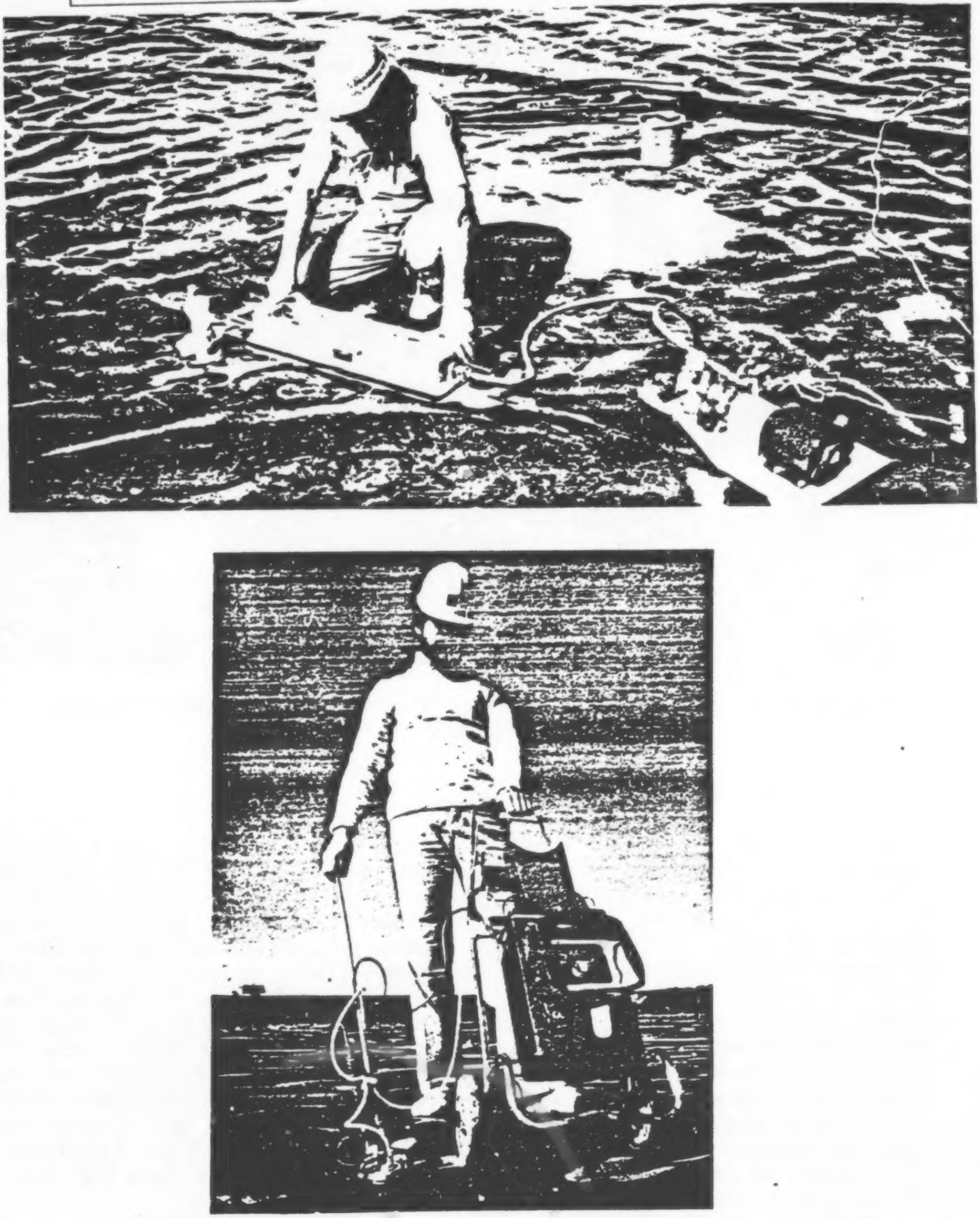


Figure 5-19. Testing the integrity of HDPE liner seams. The upper photograph (Courtesy of Gundle Lining Systems) shows the use of a "vacuum box" and the lower photograph (Courtesy of Schlegel Lining Technology) shows the use of an ultrasonic technique.

a. As a protective layer against mechanical, weather, and other environmental damage.

b. As a relatively permeable layer in landfills for the drainage and collection of leachate that is generated in the fill.

Most membrane materials have relatively little structural strength and some are quite sensitive to such environmental conditions as:

- Ultraviolet light which can degrade polymeric materials if not properly compounded.
- Infrared radiation which by heating the liner can cause evaporation of the volatile constituents and oxidative degradation of the polymer.
- Mechanical damage from solid waste primarily during placement in the field.
- Wind, which causes increased evaporation of constituents in some liner compounds, and possibly mechanical damage to the liner itself.
- Wave action in a pond or lagoon.
- Oxygen and ozone.
- Freeze and thaw.
- Hail and rain.
- Animals - hoofed, gnawing, etc.
- Vandalism.

It may be necessary to place a soil cover after installation before the filling of the facility can begin.

The need for soil covers for leachate drainage and collection purposes is discussed in Appendix V. This soil cover in addition to being a part of the drainage and collection system will also protect the liner from mechanical damage during placement and compaction of solid waste. Generally these covers are two feet or more in thickness.

The manufacturers of PVC liners recommend the placement of an earth cover to protect the liner. Ultraviolet light degrades PVC material by causing chemical changes to occur along the polymer backbone. These changes which can cause embrittlement of flexible PVC liners can be avoided or minimized by compounding the PVC with UV light absorbers and other stabilizers. However, it is recommended that PVC liners be covered regardless of the end use. Other materials, such as CSPE, CPE, EPDM, and elasticized polyolefin are recommended for exposed (noncovered) use. Manufacturers and installers of high density polyethylene and of CSPE question whether the benefit of placing a cover is worth the cost and the risk of potential damage to the liner. All polymeric membranes are susceptible to sun aging if not properly compounded. Thus, the function of a cover in this case is to block out the sun and prevent sun aging.

In addition, a cover is necessary wherever vehicular traffic is anticipated over the liner though thick liners can resist damage of light vehicles. In the case of waste impoundment facilities in which hot fluids are introduced, the cover acts to protect the liner from the initial high heat factor and subsequently to insulate the liner from residual heat by decreasing the temperature at the liquid/liner interface versus the temperature of the fluid body. In the case of a lined wastewater treatment impoundment where mechanical aeration is utilized, a cover may be required to mitigate the potential for the liner to be drawn off the bottom or side by hydraulic wave action. On-site weather conditions influence the use of a soil cover. In extreme climates, such as the northern plains or the desert Southwest, covers are often used to protect against mechanical damage due to freeze-thaw cycles and subsequent ice movement, or sun degradation. Wastewater impoundments in the northern states often become ice covered in winter. Spring thaws can result in ice movement, greatly increasing the chances for damage to an exposed liner.

Other weather conditions often dictate the necessity for special design or performance features. Hail can cause failure of some exposed liner materials, particularly on flat berms where a thermoplastic liner has been installed. Such damage can be easily prevented by the use of a soil cover. Liners exposed to high wind can be stretched and damaged by air lift, if compensations are not made in the design.

The cover for a liner can also function to reduce the impact of a chemically aggressive or incompatible waste upon the liner. This occurs because of the reduction of the liner surface area which comes in contact with the waste. Furthermore, the cover will probably also reduce the maximum concentrations of waste that contact the liner.

The type of security measures to be incorporated into the operating plan at a lined impoundment will influence the need for a soil cover. For example, if the site is not fenced and wildlife and the public have easy access to the site, then a soil cover will minimize vandalism or accidental damage. Vertical slopes prevent animals from entering the pond. One cannot build economically a fence high enough to keep deer out.

From field experience, it has been found that the maximum side slope ratio which will hold an earth cover over a smooth liner is three horizontal to one vertical. The initial covering should be placed with a light tracked bulldozer. The soil should be spread from a pile and kept at a minimum thickness of 18 inches. It is advisable that the moisture content of the bedding be kept at or below optimum moisture content so that the soil compacts readily with minimum effort. Subsequent layers of protection may be placed in a similar fashion but with larger tracked bulldozers.

The placement of the soil covers, themselves, increases the chance of puncture of the polymeric liner, and once covered, punctures cannot be repaired. The principal requirements of a cover material are that it must be free of sharp stone and other objects and that it be compatible with the waste that is to be placed on it. The cover material should be stable and resist sloughing from wave action, and should, wherever possible, be local material to keep the cost low.

Figure 5-20 shows examples of the placing of soil covers on membrane liners.

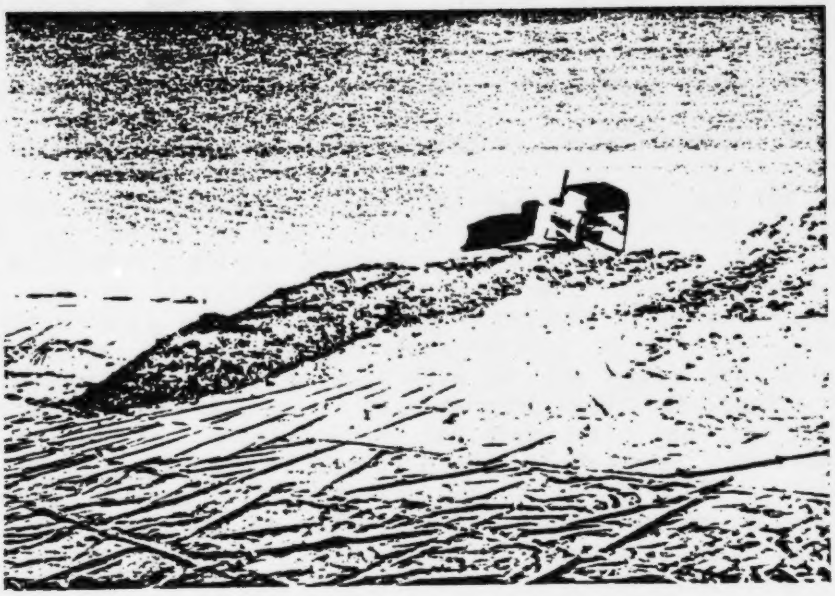
5.4.7. Use of Coupons to Monitor the Liner During Service

In light of the limited experience waste management has had with polymeric membranes in the lining of waste disposal facilities and the lack of feedback with respect to liner performance, it would be highly desirable to monitor the condition of membrane liner materials during actual service. It is recommended that samples or "coupons" of the same lot of liner material as used in a disposal facility be appropriately placed in the impoundment before the addition of the waste and be withdrawn on a planned schedule and tested. Means to accomplish such a program must be incorporated in the original design of the facility and plans made for the withdrawal and testing of the coupons during service. The coupon should be one square foot in area or larger and incorporate a field seam. Coupon placement should allow for essentially the same exposure and environment to the waste as the installed liner, safe and easy access and retrievability, economical placement, precise location, and precise identification. Thus, the design phase of a lined impoundment facility can contribute greatly to the overall success or failure of a coupon testing and evaluation program. During the construction phase, the accessibility and retrievability factors can be field tested, in addition to the determination of the adequacy of space allocated for coupons. The testing and evaluation program is a long-term ongoing procedure. Depending upon the design function and life of the impoundment, the coupon program will periodically yield information relating to the physical and chemical integrity of the liner on which decisions concerning liner replacement or liner useful life can be made. Exposure periods can range beyond twenty years or can be as short as one year.

5.4.8. Gas Venting

Certain conditions require the venting of gas that may accumulate beneath a liner. If organic matter exists in the soils under the liner, or if natural gas is present in the region, gas production is inevitable. If a pond has a flat bottom, gas will tend to accumulate under the liner. If the pressure is permitted to increase, a membrane liner can be lifted creating a cavern for additional gas accumulation. The higher the membrane bubble is allowed to rise, the more the membrane stretches and the less hydrostatic pressure is available to restrain the membrane. As a result, the membrane floats to the surface.

Venting must also be considered when a fluctuating water table is present immediately below the pond bottom. When the water table falls, void spaces in the soil under the liner are created. Air is then drawn into these voids from the surrounding soil. Conversely, when the water table rises, air which was pulled into the voids is displaced upward. The amount of fluctuation and



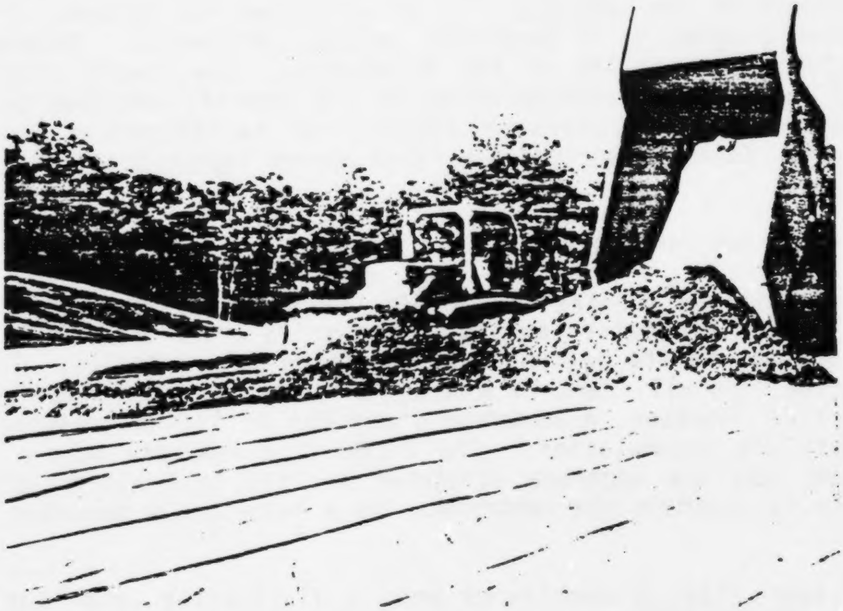


Figure 5-20. Two photographs showing bulldozers applying a soil cover over membrane liners.

proximity of the water table to the pond bottom, will dictate the reaction of the membrane to this air pumping mechanism. The need to vent this accumulating gas is best accomplished by providing a layer of uniformly graded sand of which less than 5% by weight will pass the 200 sieve. Also for membrane liners, a geotextile may be used, which allows gas to pass through the fabric's cross-section under a surcharge load. In order for these media to be effective, the bottom of the pond must slope up from its lowest point to the toe of the dike a minimum of 2% and the liner must be reinforced with a fabric scrim. The venting medium is carried across the entire bottom, up the side slopes. Venting to the atmosphere is accomplished through gas vents located on the inside slope of the berm, approximately one foot down from the crown of the dike. Simplified representations of two designs of gas vents for membrane liners are illustrated in Figure 5-21.

5.5 PLACEMENT OF MISCELLANEOUS TYPES OF LINERS

5.5.1 Sprayed-on Liners

A basic problem in the placing of this type of liner is to make it pinhole free. Spray-on liners require a more carefully prepared subgrade than other liner types. The subgrade is dragged and rolled to produce a smooth surface free from rough, irregular or angular projections. If the surface cannot meet the above criterion, a fine sand or soil padding may be necessary for proper membrane support. The site should be excavated or over-excavated and side slopes flattened to allow for any padding necessary before liner application and for 1 to 3 feet of cover over the membrane (Bureau of Reclamation, 1963, p. 80-82).

Sprayed-on catalytically-blown asphalt membranes are heated to 200-220°C (392-428°F) and applied at a rate of 1.5 gal/yd^2 measured at 60°F. The high softening point asphalt should not be overheated since this may lower the softening point and change other properties of the material. The spray bar is usually set off to the side of the distributor so that the heavy equipment does not travel over the subgrade or newly applied membrane. To eliminate pinholes, it is recommended that three passes be made at a rate of 0.5 gal/yd^2 each for a cumulative application of 1.5 gal/yd^2 (Asphalt Institute MS-12, 1976). The final membrane is usually about 1/4 inch thick. Sections of membrane should be overlapped 1 to 2 feet. The newly applied hot asphalt melts the underlying layer; both cool to form one continuous liner. The asphalt cools quickly and the next pass with the spray bar may be made immediately after finishing the previous layer. Care should be taken to avoid the accumulation of sand, silt, dust, or gravel on the asphalt between applications. Foreign materials on the membrane prevent proper bonding of layers and may cause pinholes to form.

The property of rapid cooling and hardening also presents some problems in applications. Skill and organization are required to prevent freezing of asphalt in the lines. Spray bars should not be turned off for more than one or two minutes at a time. All pumps, lines and bars should be cleaned with air or distillate after each spraying operation (Day, 1970). Figure 5-22 illustrates large scale spraying equipment and the spraying of rubberized asphalt.

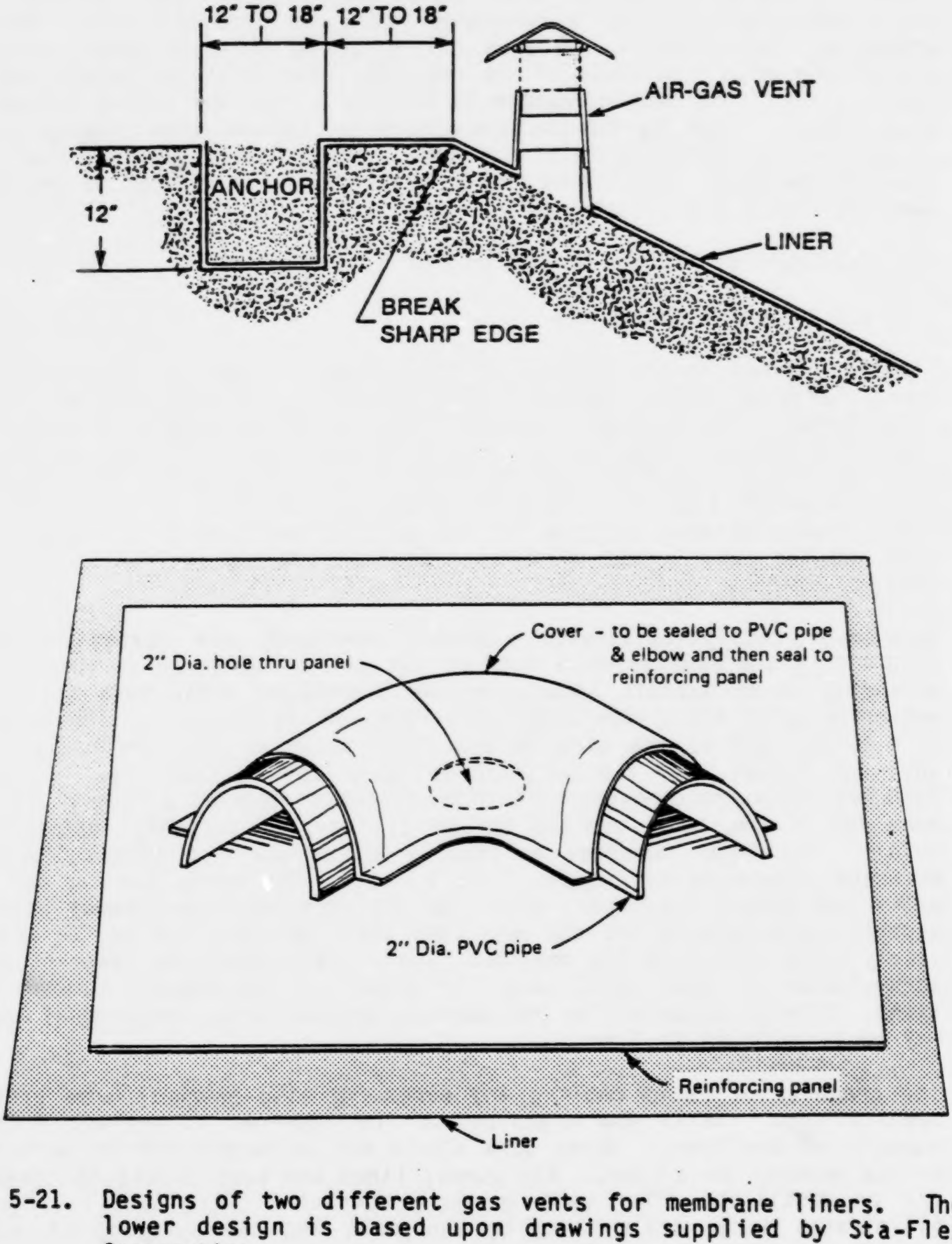
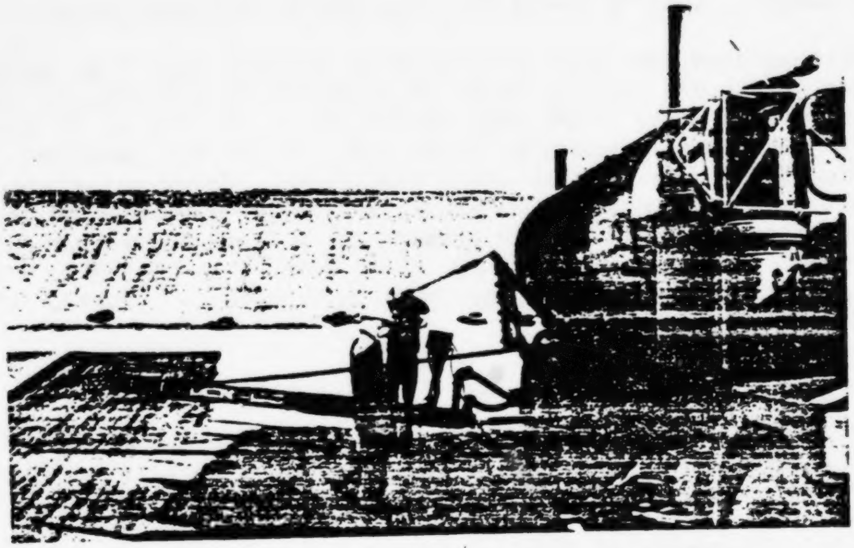

12" TO 18"
12" TO 18"
AIR-GAS VENT
ANCHOR
12"
LINER
BREAK SHARP EDGE
Cover - to be sealed to PVC pipe & elbow and then seal to reinforcing panel
2" Dia. hole thru panel
2" Dia. PVC pipe
Reinforcing panel
Liner

Figure 5-21. Designs of two different gas vents for membrane liners. The lower design is based upon drawings supplied by Sta-Flex Corporation.

Reproduced from
best available copy.



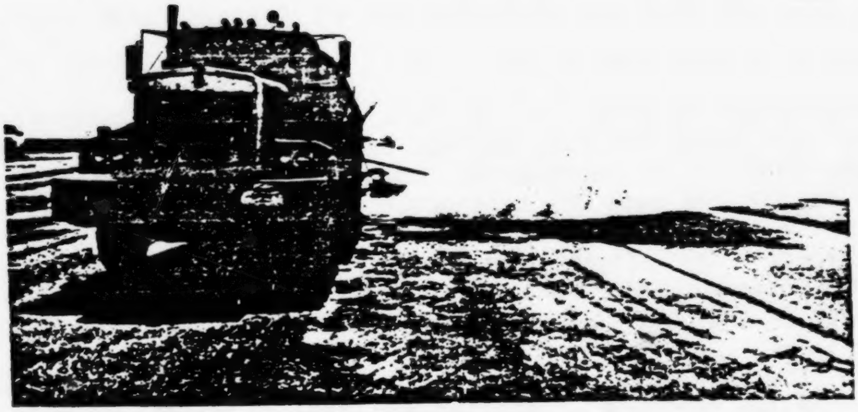


Figure 5-22. Placement of sprayed-on liners. The upper photograph shows a spray bar attached to a tanker truck and the lower photograph shows the spraying of a rubberized asphaltic membrane (Courtesy of Arizona Refining Company).

Asphalt emulsions are sprayed at ambient temperatures (above freezing), usually onto a supporting fabric of jute, glass or synthetic fiber. A continuous membrane forms after the emulsion breaks and the water evaporates. Several light applications are used, not only to avoid pinholes, but to allow drying between coats to avoid porosity due to entrapped water.

Asphalt membranes are usually covered to protect them from mechanical damage. Cover materials are usually earth or graded earth and gravel. Membrane damage and leaks can occur from poor application or choice of cover material. Blading the cover frequently folds the top of the membrane and should be avoided. Rocks can tear or gouge the liner. Cover materials should not be applied if the temperature is below 32°F since the membrane may rupture from the operation (Day, 1970). Placement of a fine grained soil cover by draglines should be done on the floor first then from bottom to top of the side slopes. Coarser materials may then be applied. (Bureau of Reclamation, 1963, pp. 82-83).

5.5.2 Placement of Soil Sealants

Asphalt emulsions may be injected into the subsurface. Special equipment is used to inject the liquid six inches below the surface to form a continuous membrane about 1/2 inch thick.

5.5.3 Placement of Chemisorptive Liners

Chemisorptive liners vary in form and type. Some are soil sealants, liquids or powders, which are applied using methods similar to those used for bentonite or sprayed-on liners. Others are pozzolanic or cement-like. These are installed and constructed following procedures similar to those used for asphalt concrete or cement. Individual manufacturers or producers should be addressed with questions concerning this class of liners.

5.6 LINERS AND LEACHATE MANAGEMENT FOR SOLID WASTE LANDFILLS

5.6.1 Environment of the Liner in a Sanitary Landfill

The environment in which a liner must function will ultimately determine how well it can serve for long periods of time. The situation of a liner in a sanitary landfill is represented schematically in Figure 5-23. Some of the conditions at the base of a landfill should have no adverse effect on life expectancy of a given material, whereas other conditions could be quite deleterious. The effects can be different for different materials. Some important condiditons that exist at the bottom of a MSW landfill in the proximity of the liner and that may influence the life of a liner are:

1. The barrier is placed on a prepared surface that has been graded, to allow drainage, compacted and free of rocks, stumps, etc., but may settle to cause cracking of hard liners. A brittle or weak material might fall.

2. Anaerobic condition with no oxygen to cause oxidative degradation.

3. No light, which normally degrades many polymeric materials.

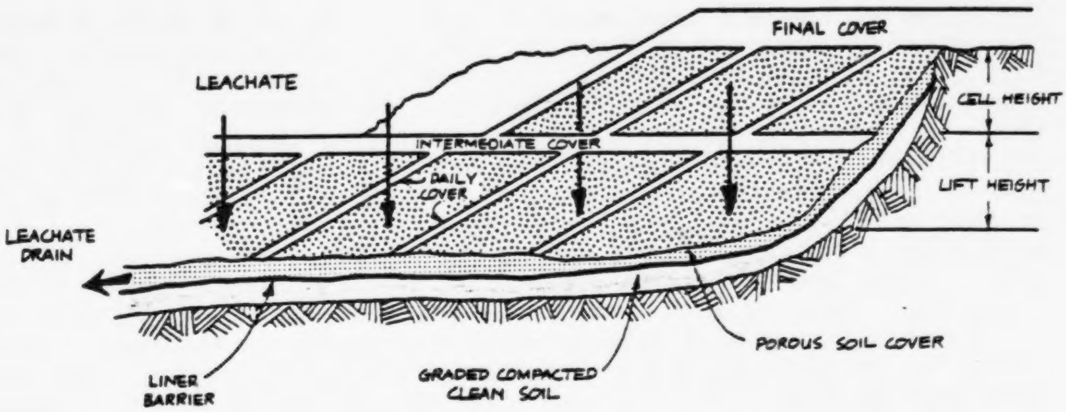

FINAL COVER
LEACHATE
CELL HEIGHT
INTERMEDIATE COVER
DAILY COVER
LIFT HEIGHT
LEACHATE DRAIN
POROUS SOIL COVER
LINER BARRIER
GRADED COMPACTED CLEAN SOIL

Figure 5-23. Schematic drawing of a lined sanitary landfill (Haxo, 1976).

4. Generally wet-humid conditions, particularly if leachate is being generated regularly, that could result in the leaching of ingredients from a liner.

5. Cool temperatures of 40 to 70°F normally, although high temperatures can be generated within the fill if aerobic decomposition takes place.

6. Generally acidic conditions from the leachate due to presence of organic acid.

7. High concentration of ions in the leachate that may exchange with clay soil and increase permeability.

8. Considerable dissolved organic constituents in the leachate that may swell and degrade some of the organic material liners.

9. Only modest head pressure, since drainage above the liner is designed to take place continually. A porous soil is placed on top of the liner before refuse is placed.

10. The presence of the gases, carbon dioxide and methane, generated in the anaerobic decomposition of the refuse. The carbon dioxide is probably dissolved in the leachate and contributes to its acidity. It may cause mineralization of the soil in the area of the liner.

The effects of these environmental conditions will differ on the various barrier materials. However, it appears at present that mechanical failure during installation or during operation of the fill due to settling of the soil may be the most significant source of failure of a liner.

5.6.2 Estimating Leachate Volume

The volume of leachate produced at a landfill site is primarily a function of the amount of water that flows through the refuse; in general, the more that flows through the refuse, the more pollutants will be leached out. Precipitation is a key factor affecting the volume of leachate produced; thus, in regions of moderate-to-heavy rainfall, leachate generation can be significant. For the designer of landfill leachate collection systems, however, a qualitative assessment that "significant leachate will be produced at this site" is not sufficient. What is needed, rather, is a tool for predicting with a reasonable degree of accuracy the quantity of leachate that a given landfill can be expected to produce under a number of different scenarios. Fortunately, within the last several years, such a tool has evolved, based on a water balance method developed by Thornthwaite and Mather (1955) in the soil and water conservation field. A computer model has been developed to simulate hydrologic characteristics of landfill operations (Perrier and Gibson, 1982).

The water balance method is a kind of mathematical accounting process which considers precipitation, evapotranspiration, surface runoff, and soil moisture storage, all of which have a bearing on the extent to which infiltration can be expected to occur after a rain. Since infiltration is the major contributor to leachate generation, knowing how much can be expected under a given set of site conditions will provide the designer with valuable information on which to base his recommendations. Such recommendations might specify the soil types, drainage grades, plant species, or cover thicknesses required to minimize or preclude leachate production. Similarly, leachate sumps, risers, pumps, and treatment facilities can also be more rationally engineered once a water balance calculation has been made.

Three factors are of critical importance in a water balance calculation: soil moisture storage, evapotranspiration and surface water runoff. The first is critical because a cover soil that has exceeded its field capacity (the maximum amount of water a soil can retain in a gravitational field without downward percolation) becomes a source of infiltration to the refuse which may eventually lead to leachate production. Ideally, efforts by the design engineer should be directed to ensuring that the cover soils and other landfill features are selected and installed so as to keep the soil moisture storage below field capacity. Assuming there is no groundwater infiltration or other source of excess liquids, leachate production should not occur. Obviously, some hydrologic regimes such as high rainfall and low evapotranspiration make it uneconomical to achieve this condition at all times; emphasis must then be shifted to determining how much leachate is apt to be produced and what control-recovery-treatment options can be employed.

The amount of water that can be added to solid waste before reaching field capacity depends on the moisture content of the waste at the time of placement in the landfill. Moisture content at time of placement is not a constant, but a function of waste composition, density and climatic conditions. However, as a rule of thumb, moisture content of the wastes at the time of placement has been found to range from 10 to 20 percent by volume (Fenn et al, 1975).

As Table 5-4 indicates, refuse has a large capacity to absorb moisture before leachate is produced. Leachate production will not occur at rates equal to infiltration of rainfall until saturation is exceeded, a condition significantly above field capacity. However, leachate production can occur by channeling, a process by which net infiltration flows through openings or channels within the refuse before the field capacity of the fill is reached.

TABLE 5-4. MOISTURE CONTENT OF REFUSE[a]
(Average Values)

Refuse at	Percent by volume	Equivalent inches H_2O/ ft of refuse	Equivalent gallons H_2O/ yd^3 of refuse
Placement	10-20%	1.8"	30
Field capacity	20-35%	3.6"	60
Saturation[b]	--	6.6"	110

[a] Adapted from: Fenn et al., 1975.

[b] Based on a 0.4 porosity for refuse.

The second most important variable, evapotranspiration, represents the amount of water present in the soil that is lost to the atmosphere from a given area through direct evaporation from the soil and transpiration from plant tissues. When soil moisture is at or near field capacity, evapotranspiration occurs at its maximum potential rate. However, as soil moisture approaches the wilting point (the moisture content below which moisture is unavailable for withdrawal by plants), the amount of water available begins to restrict the rate of evapotranspiration, resulting in reduced actual water losses. The water balance process takes this effect into account. While rates of evapotranspiration for different parts of the country have been developed by Thornthwaite and Mather (1964), their method may not provide the best estimate for all areas of the country. Thus, the design engineer has to evaluate Thornthwaite's figures versus other evapotranspiration data that could be applied to each particular area of interest.

The third parameter of major importance is surface runoff, i.e. that portion of rainfall which will run off the site in lieu of entering the cover soil. Variables affecting runoff include intensity and duration of rainfall, existing soil moisture, soil permeability, slopes, and type of vegetative cover. Runoff can be calculated using empirical runoff coefficients commonly used to design surface water drainage systems. By multiplying the coefficients by the mean monthly precipitation, a "mean monthly surface runoff" can be calculated.

Details on the actual calculations involved in using the water balance method are presented in the appendix to an October 1975 EPA report (EPA-SW-168). In brief, the basic equation for determining the amount of percolation anticipated at the given site is as follows:

$$PERC = P - R/O - ST - AET$$

where,

PERC = Percolation, i.e. the liquid that permeates the refuse.

P = Precipitation for which the mean monthly values are typically used.

R/O = Surface runoff

ST = Soil moisture storage, i.e. moisture retained in the soil after a given amount of accumulated potential water loss or gain has occurred.

AET = Actual evapotranspiration, i.e. actual amount of water loss during a given month.

In using the water balance method to quantify the volume of leachate produced, special field conditions at landfill sites should be considered. Variations in cover depth and the absence of vegetation in some areas of the site will influence leachate production. More percolation thus occurs during the operational phase due to such factors as absence of vegetation, shallow depths of intermediate cover, surface cracks and lack of adequate drainage. As a result, leachate may be produced sooner and in greater volume than was predicted by water balance calculations based on a completed landfill. Another special condition that can result in a greater production of leachate than was predicted by the water balance method is irrigation of the completed site for a specific use such as a park or agricultural area. Since the irrigation required to supply evapotranspirative demands of the growing vegetation is not totally efficient, percolation can be significant and hence leachate production can result. An additional field condition that can have an impact on the water balance calculations is the presence of frozen ground and/or snow accumulation. Such a condition reduces the infiltration of the precipitation during winter months with the net effect on the water balance of decreasing percolation and hence the quantity of leachate produced.

To illustrate the application of the water balance method in a variety of climatic conditions, Table 5-5 summarizes data for the key water balance parameters in three regions of the United States: Midwest, Southeast, and Southwest. As the table indicates, the range of values for percolation of moisture into refuse can vary widely depending on whether the site is in a humid climate such as that found in the Midwest, or an arid climate, such as that of Los Angeles.

Once the designer has estimated by means of the water balance method the quantity of moisture that will percolate into the refuse, he is in a position to make a decision concerning the type and size leachate collection facilities. Applications of the water balance method to landfills in a broad range of climatological conditions in the continental United States has shown a range of percolation rates of 15 inches per year to 36 inches per year (assuming proper covering, vegetation, and drainage of the completed landfill surface). These values provide a rule of thumb for use by the designer in sizing leachate collection systems.

TABLE 5-5 SUMMARY OF WATER BALANCE CALCULATIONS[a]

	Local soil conditions	Precipitation, mean annual cm (in)	Surface runoff coefficient	Percolation mean annual, cm (in)	Percolation, maximum monthly, cm (in)
Cincinnati, Ohio	Clay Loam	102.5 (40.4)	0.17	21.3 (8.4)	6.6 (2.6)
Orlando, Florida	Sandy Loam	134.2 (52.8)	0.075	7.0 (2.76)	2.5 (1)
Los Angeles, California	Silty Loam	37.8 (14.8)	0.15	0	0

[a] Source: Fenn et al., 1975.

The major advantage of the water balance method is its flexibility in allowing for modification of various input variables. This enables designers to compare the effectiveness of alternative control techniques by simply "running" the water balance model for each management plan. When used in conjunction with data on leachate quality and probably water quality impacts, the water balance is an extremely effective tool.

Figure 5-24 illustrates the factors influencing percolation that may be manipulated using the water balance method as a leachate management tool; thus, by increasing several of the water balance variables, e.g. a final cover of low permeability, leachate generation may be precluded. As shown in Figure 5-25, surface runoff, soil moisture storage, and evapotranspiration - key parameters in the water balance equation - can be readily increased, thereby reducing percolation of liquid into the wastes. Surface runoff can be enhanced by (1) increasing drainage gradients, (2) selecting more impermeable cover soil, (3) using a thicker and denser cover soil, (4) utilizing synthetic membranes, (5) adding soil conditioners (chemicals, bentonite, etc.) to render the existing cover soil less permeable, and (6) implementing a good maintenance program for graded surfaces. Like surface runoff, potential soil moisture storage can be increased by using thicker cover soil and by employing silt and clay cover. Selecting highly evapotranspirative vegetation that is tolerant to landfill conditions enhances evapotranspiration. Landfill slopes must be graded to enhance runoff while minimizing erosion. The final surface of a landfill should be sloped sufficiently to prevent water from pooling over the surface (a minimum slope of 2% is recommended).

As noted earlier, not all climates and hydrogeologic environments enable practical/economical prevention of leachate generation. Thus, in humid climates where leachate generation is more difficult to preclude, the hydrogeology of the site should be carefully evaluated to determine the potential for natural inhibition of leachate production. At sites where the hydrogeologic conditions are incapable of minimizing the impact of leachate on underlying ground water, leachate collection facilities should be employed. Design criteria for such facilities are discussed in the next section and Appendix V.

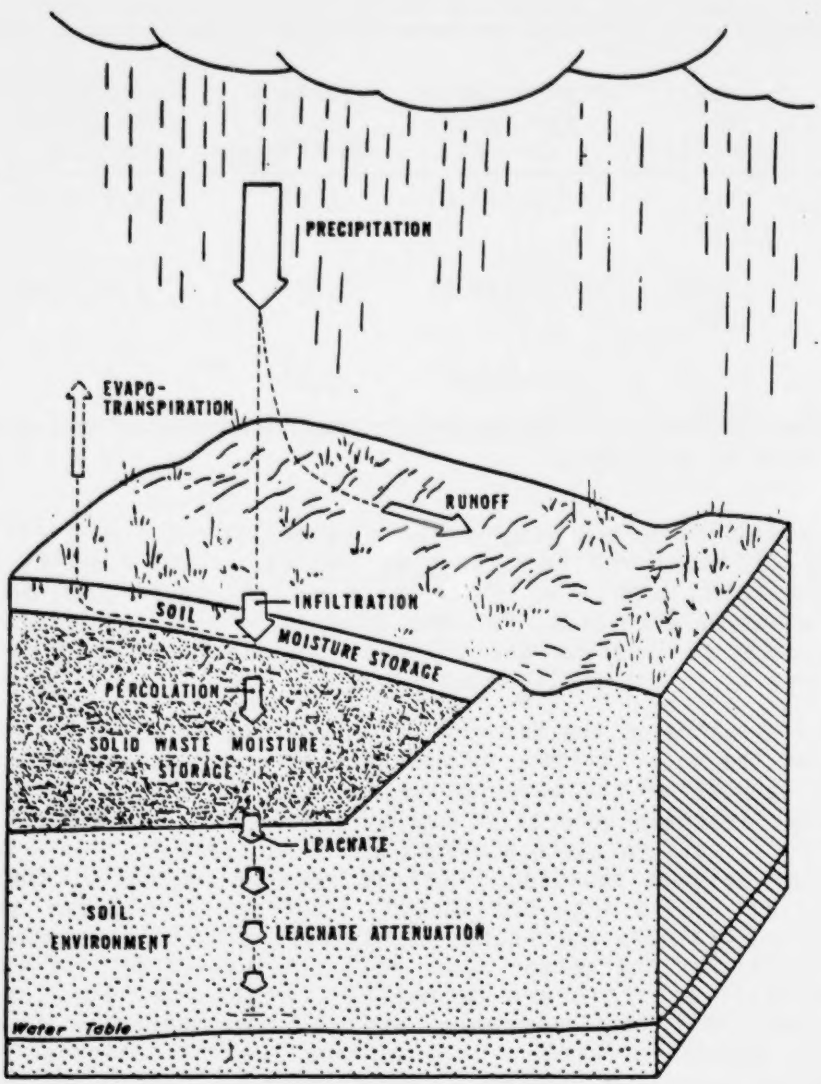

PRECIPITATION
EVAPO-
TRANSPIRATION
RUNOFF
INFILTRATION
SOIL
MOISTURE STORAGE
PERCOLATION
SOLID WASTE MOISTURE
STORAGE
LEACHATE
SOIL
ENVIRONMENT
LEACHATE ATTENUATION
Water Table

Figure 5-24. Percolation through solid waste and movement of the leachate into the soil environment.

5.6.3 Transmissivity of Leachate

When the infiltration of precipitation and other sources of water applied to the landfill surface exceed the combined effects of runoff, evapotranspiration, and soil moisture storage, leachate will be produced in the landfill. This net inflow to the landfill, termed percolation on Figure 5-24, is absorbed by the waste until the field capacity of the fill is reached, field capacity here defined as the maximum amount of moisture a soil or solid waste can

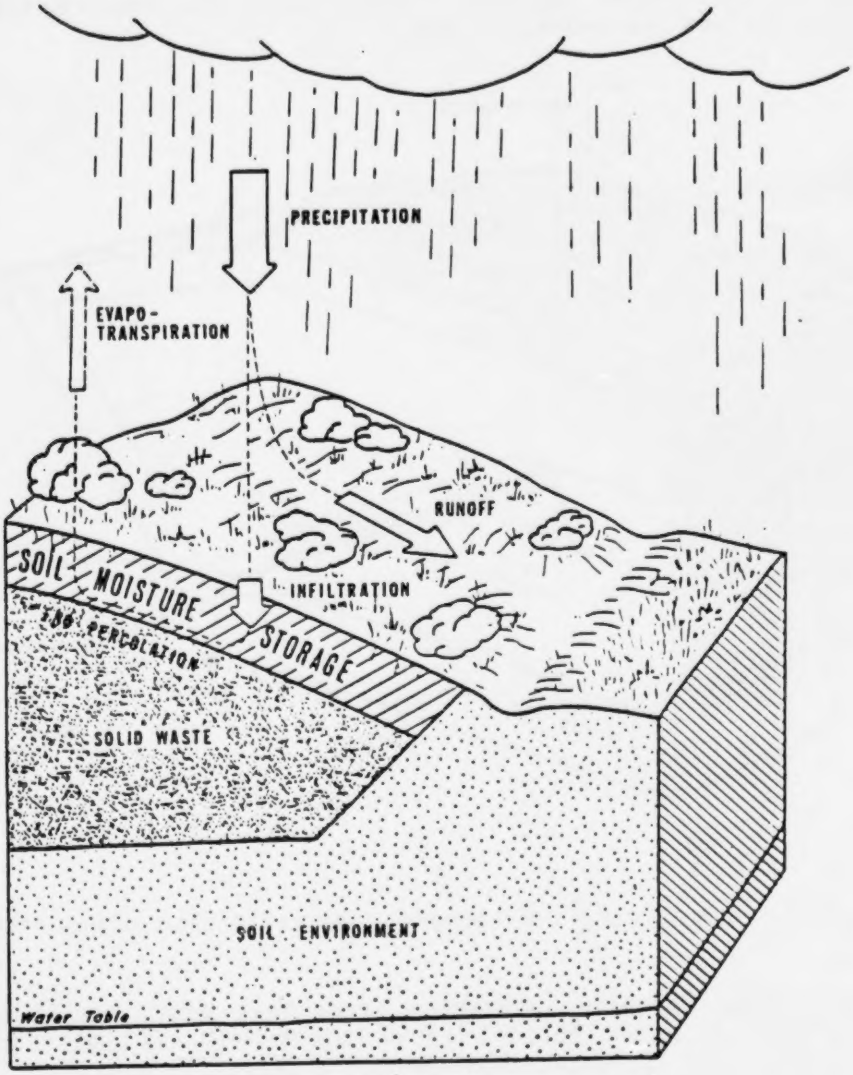

PRECIPITATION
EVAPO-TRANSPIRATION
RUNOFF
INFILTRATION
SOIL MOISTURE STORAGE
PERCOLATION
SOLID WASTE
SOIL ENVIRONMENT
Water Table

Figure 5-25. Preclusion of leachate production through use of proper drainage grades and cover.

retain in a gravitational field without producing a continuous downward percolation (Fenn et al., 1975). Thereafter, percolation into the fill will accumulate as leachate at the base of the fill or discharge to the soil-groundwater regime beneath the landfill (see Figures 5-26 and 5-27).

When percolation occurs in a landfill located within a containment lined with natural soil, constructed admixes, remolded clay soil, or manufactured membranes, leachate will accumulate in the fill. Eventually, the leachate level will rise until (1) the head created on the base of the landfill results in an unacceptable rate of discharge through the liner, or (2) it threatens to discharge to the ground surface. Both conditions require the removal of leachate to relieve the hydraulic head.

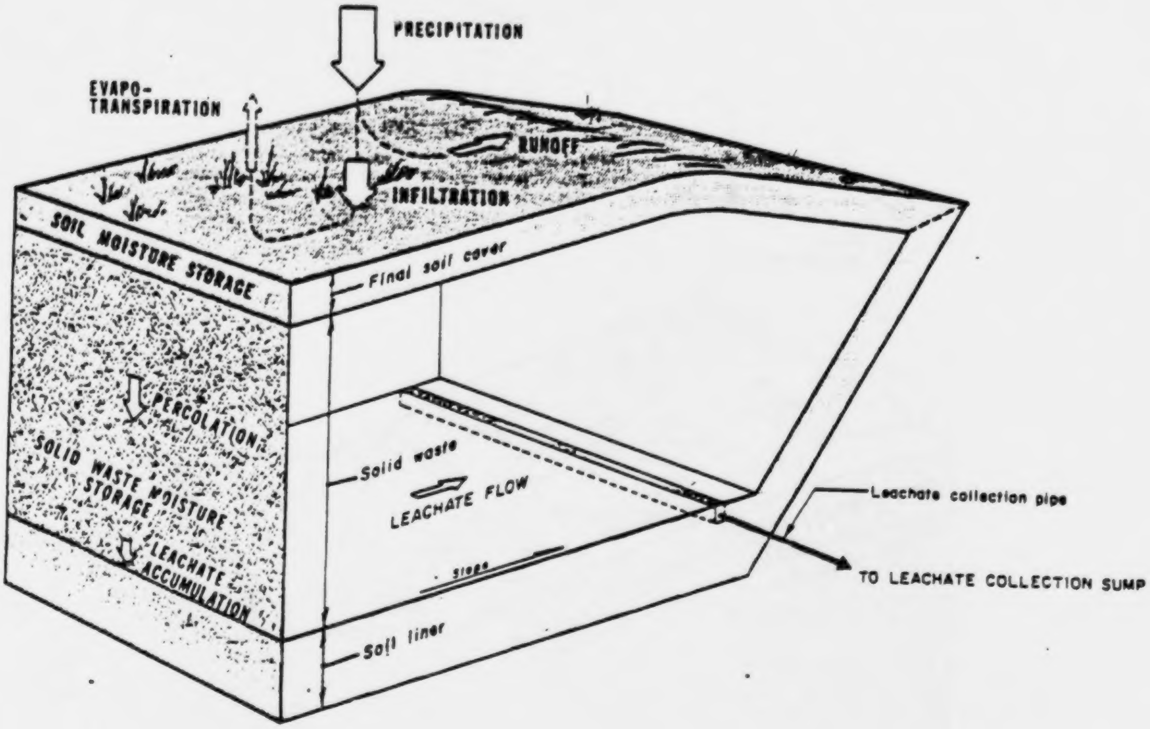

PRECIPITATION
EVAPO-TRANSPIRATION
RUNOFF
INFILTRATION
SOIL MOISTURE STORAGE
Final soil cover
PERCOLATION
SOLID WASTE MOISTURE STORAGE
Solid waste
LEACHATE FLOW
LEACHATE ACCUMULATION
Slope
Soil liner
Leachate collection pipe
TO LEACHATE COLLECTION SUMP

Figure 5-26. Accumulation, containment, and collection of landfill leachate.

Figure 5-27 shows leachate saturation lines that would result under conditions of leachate accumulation: (1) no withdrawal, (2) withdrawal through waste fill only, and (3) withdrawal through a permeable medium.

Removal of leachate is accomplished by draining to a leachate collection system consisting of perforated pipes installed in gravel-filled trenches and discharging to sumps from which the leachate is pumped. The rate at which the leachate is removed is directly related to the permeability of the media through which the leachate must flow to the collection system. The permeability and porosity (percent of voids of potential fluid storage) of various soil materials and municipal waste fill are shown on Figure 5-28.

When the geohydrologic conditions beneath the fill require minimization of the leachate head, leachate removal to sumps can be enhanced by the placement of a highly permeable material such as sand or a geotextile over the base of the landfill.

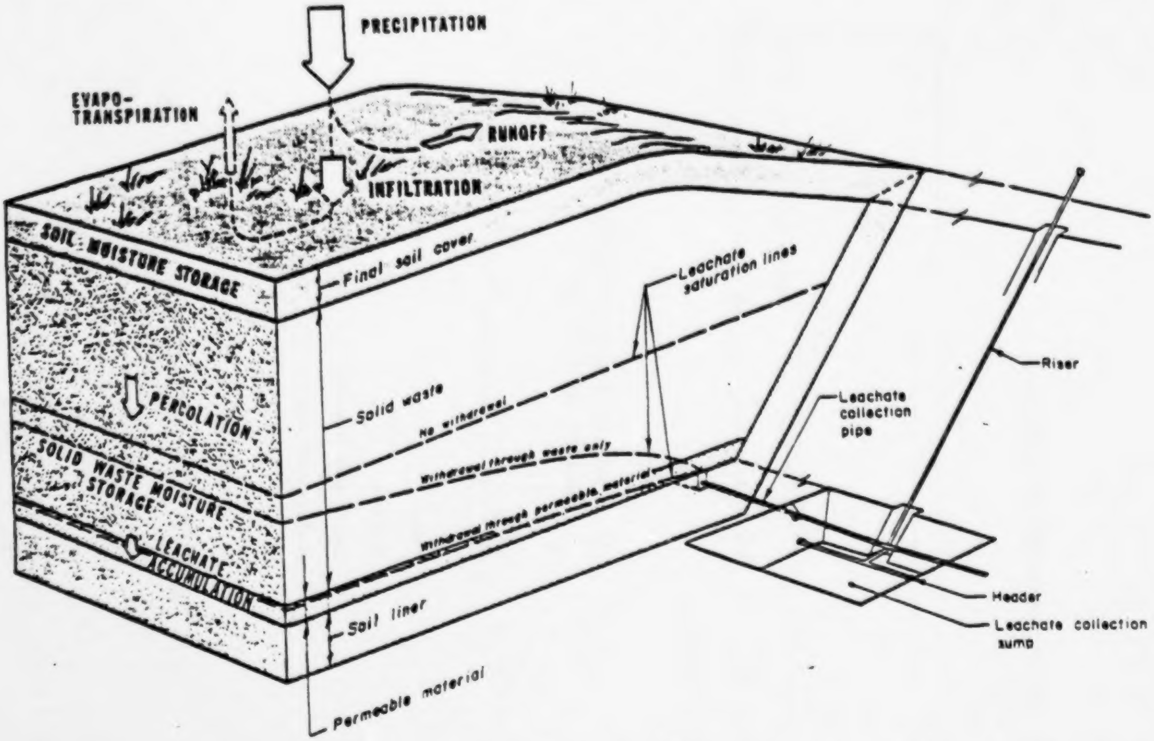

PRECIPITATION
EVAPO-
TRANSPIRATION
RUNOFF
INFILTRATION
SOIL MOISTURE STORAGE
PERCOLATION
SOLID WASTE MOISTURE STORAGE
LEACHATE ACCUMULATION
Final soil cover
Leachate saturation lines
Solid waste
No withdrawal
Withdrawal through waste only
Withdrawal through permeable material
Soil liner
Permeable material
Leachate collection pipe
Riser
Header
Leachate collection sump

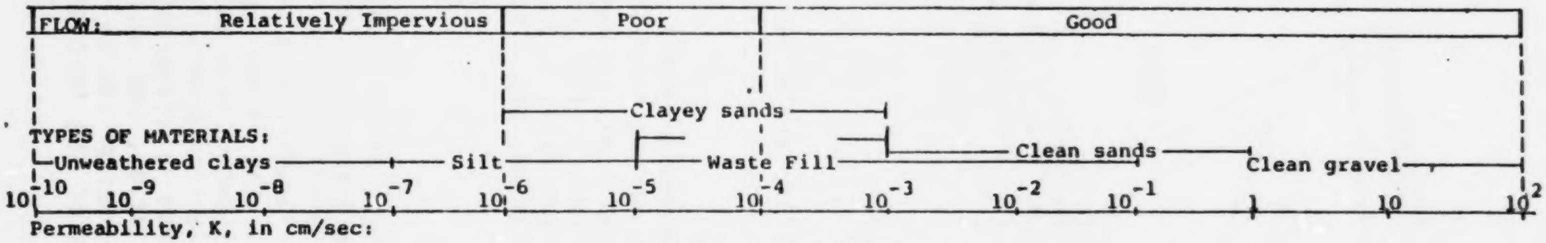
Figure 5-27. Accumulation, containment, collection, and withdrawal of landfill leachate showing saturation levels for different conditions.

Figure 5-29, based on a flow net solution, provides a method of determining the maximum head that will result in a medium given the permeability, spacing of leachate collection pipes, and percolation rate into a saturated fill. The analysis assumes gravity flow to a water surface in the collection pipe maintained below the base of the fill and a uniform daily percolation rate to the withdrawal saturation line. Example calculations are also presented on Figure 5-29.

5.6.4 Leachate Collection System Network

A leachate collection system generally consists of strategically placed perforated drain pipe bedded and backfilled with drain rock. The pipe can be installed in a trench or on the base of the landfill. The system can be installed completely around the perimeter of the landfill or a complex network or grid of collection pipes can be installed - the latter being used when the areas involved are very large and/or the allowable head buildup is quite small (see Sec. 5.6.3 Transmissivity). The collection system is drained to a sump or a series of sumps from which the leachate is withdrawn. Appendix V discusses in detail the layout, sizing, installation, and selection of pipe material for leachate collection systems. A series of charts and tables are presented for use in the design and analysis of the leachate collection system.

PERMEABILITY, POROSITY AND DRAINAGE CHARACTERISTICS OF MATERIALS



a) DRAINAGE CHARACTERISTICS:

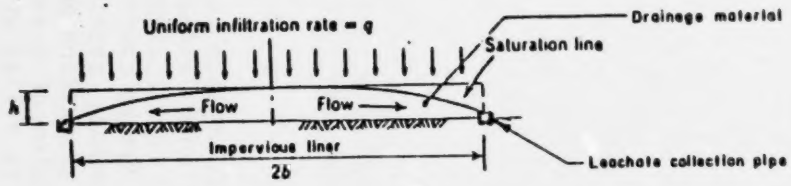
b) AVERAGE PERMEABILITY VALUES FOR VARIOUS MATERIALS:

	COEFFICIENT OF PERMEABILITY	
TYPE	cm/sec	ft/day (calc)
very fine sand	5×10^{-3}	10
fine sand	2×10^{-2}	50
concrete sand	2.0×10^{-2}	50
fine to medium sand	5×10^{-2}	150
medium sand	10^{-1}	250
medium to coarse sand	1.5×10^{-1}	400
gravel and coarse sand	3×10^{-1}	850
clean gravel	10	3.0×10^{4}
concrete gravel	25	7.0×10^{4}

c) RANGE OF POROSITY VALUES FOR VARIOUS MATERIALS:

TYPE	Porosity %
clay	45 - 55
sand	35 - 40
gravel	30 - 40
sand and gravel	20 - 35
municipal waste	30 - 40

Figure 5-28. Selected characteristics of soils and waste fills (Cedergren, 1967; Davies and DeWiest, 1966; Freeze and Cherry, 1979; Sowers, 1979; Todd, 1959).


Uniform infiltration rate = q
Drainage material
Saturation line
h
Flow
Flow
Impervious liner
2b
Leachate collection pipe

(a) Cross section of landfill surface

For leachate flow conditions represented in Fig. a, the following equation approximates the flow net solution:

$$q/K = (\frac{h}{b})^2$$

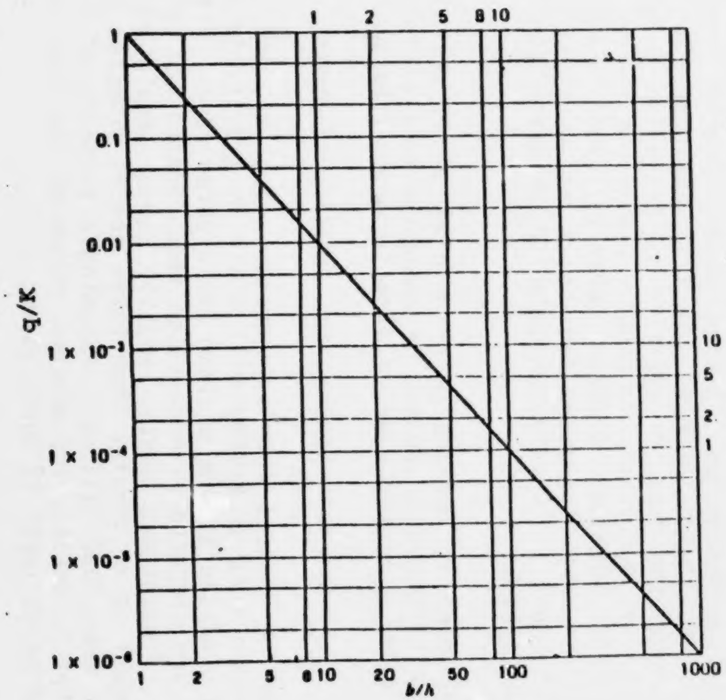
WHERE:
q = uniform infiltration rate
K = coefficient of permeability
h = head of leachate above impervious liner
b = width of area contributing to leachate collection pipe

EXAMPLE 1.

For waste overlying the liner; with collection pipes at 200' interval spacings:
q = 2"/month = .00548'/day
K (wastes) = 10^{-3} cm/sec = 2.83'/day
b = 100' and q/K = 2 x 10^{-3}
from chart; b/h = 20; therefore, the head (h) acting on the liner = 5'

EXAMPLE 2.

For a 1' thickness of permeable material overlying soil liner:
q = 2"/month = .00548'/day
K (sand) = 2 x 10^{-2} cm/sec = 50'/day
b = 100' and q/K = 1 x 10^{-4}
From chart, b/h = 100; therefore, the head (h) acting on the liner = 1'



(b) Uniform infiltration rates vs. b/h for drainage material

Figure 5-29. Determination of leachate head on impervious liners using flow net solution (Cedergren, 1967). Figure (b) is a log-log plot with subdivisions shown on the right and top of graph.

The spacing of leachate collection pipes will influence the maximum head of leachate on the base of the fill, given a uniform rate of leachate percolation to a saturated fill and the permeability of the medium through which the leachate is withdrawn. The configuration of the collection pipe network varies depending on the head allowed over the landfill base liner: the greater the allowable head, the greater the pipe spacing. As a minimum, the leachate collection system should extend completely around the perimeter of the site to provide absolute control of the level to which leachate can rise on this critical boundary.

An interior grid system becomes necessary if the leachate head on the base of the fill must not exceed a specified value. The slopes and spacing of the interior grid pipes are controlled to a large degree by the minimum base slope of one percent. Placement of a layer of permeable material over the base of the fill, coupled with the use of an interior collection pipe grid, may be necessary in extreme cases where the development of a leachate head cannot be tolerated.

5.6.5 Leachate Withdrawal and Monitoring Facilities

Landfill leachate control systems must include facilities for (1) the monitoring of leachate levels at the base of the landfill and (2) the withdrawal of leachate to prevent buildup of a liquid level that would promote unacceptable migration of leachate from the landfill.

The current state-of-the-art in landfill design uses sumps or excavated basins located at low points on the base of the landfill to which a leachate control system discharges. A riser pipe extending from the sump to the ground surface or to the surface of the fill provides the means for removing the leachate from the sump in addition to providing a "well" in which leachate levels can be measured. Leachate sumps are filled with drain rock that provides the necessary storage capacity (pore space) while also presenting transmissibility characteristics necessary to produce flow to the withdrawal pump at a rate adequate to maintain the gravity flow from the collection system.

The riser pipe is perforated or slotted along the section immersed in the drain rock filled sump and may be connected to a perforated header pipe in the sump to allow a higher rate of flow to, and withdrawal from, the riser pipe.

5.6.5.1 Spacing and capacity of sumps

Sumps must be located with a frequency, capacity, and configuration such that the leachate control system will drain by gravity to the sump when leachate is being produced at the maximum anticipated rate. Frequently, the locations of sumps are dictated by excavation requirements and collection system configurations. Hazardous waste landfill sumps should have a leachate storage volume equal to or greater than three months expected leachate production but not less than 1000 gallons. Assuming a porosity of 0.4 (fraction of gravel volume that is voids), the minimum volume of the sump that will be filled with rock must be at least 12 cubic yards.

The drain rock must be (1) free of fines that could reduce the transmissivity of the rock, (2) of a sufficiently coarse gradation so it does not enter the perforations or slots in the withdrawal pipe, (3) nonsoluble in an acid environment and (4) sufficiently protected from fines entering from adjacent soil and/or refuse. Satisfactory performance can be expected (Young et al, 1982) if the drain rock gradation and perforation, diameter, or slotting width selected for the drain pipe satisfies the following U. S. Army Corps of Engineers (1955) criteria for gradation of filter materials in relation to pipe openings:

For slots:

$$\frac{D_{85}\text{ filter material}}{\text{slot width}} = 1.2$$

For circular holes:

$$\frac{D_{85}\text{ filter material}}{\text{hole diameter}} = 1.2$$

The Bureau of Reclamation (1973) uses the following criterion for grain size of filter materials in relation to openings in pipes:

$$\frac{D_{85}\text{ of the filter nearest the pipe}}{\text{maximum opening of drain pipe}} = 2\text{ or more}$$

where D85 is the screen size through which 85% of the drain rock (by weight) could pass.

Cedergren (1967) suggests that the above equations represent a reasonable range over which satisfactory performance can be expected.

Figure V-2 in Appendix V can be used to determine the required sump capacity or withdrawal rates needed to ensure gravity flow from the leachate collection system under the maximum discharge rate. To determine the required capacity or withdrawal rate (1) locate on Figure V-1, also in Appendix V, the percolation rate that has been previously calculated by the water balance method, (2) rise vertically from the horizontal axis to the line corresponding to the average width of area tributary to the leachate collection pipe(s), and (3) move horizontally from the junction in (2) above to the vertical axis and read the flow per 1000 feet of collection pipe tributary to the sump.

5.6.5.2 Monitoring and withdrawal

The riser pipe extending from the leachate sump must be of a diameter that will accommodate a pump suction line in shallow facilities or a submersible pump or air pump when the depth to the sump is greater than 20 to 25 feet. Due to the corrosive nature of leachates, inert pipe materials such as PVC or the equivalent should be used. The riser pipe can be installed in a trench excavated in the wall of the landfill or disposal trench excavation to protect the pipe from construction damage and stresses due to settlement of the fill. Alternatively, the riser can be installed vertically from the sump. To protect the riser pipe, it is advisable to install vertical risers within a larger diameter protective casing with the annular space filled with sand or fine gravel.

Typical construction details for leachate monitoring and withdrawal wells with vertical and inclined risers are shown on Figures 5-30 and 5-31 respectively.

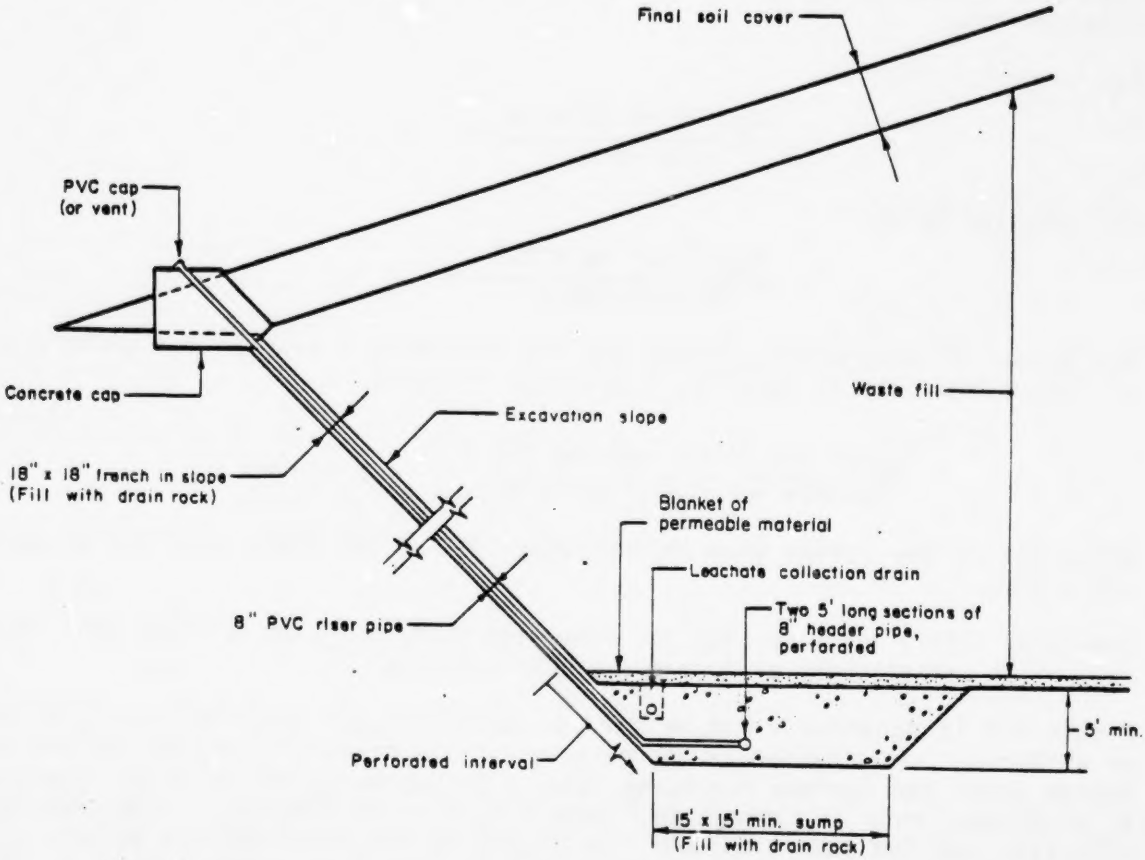

Final soil cover
PVC cap
(or vent)
Concrete cap
Waste fill
Excavation slope
18" x 18" trench in slope
(Fill with drain rock)
Blanket of
permeable material
Leachate collection drain
Two 5' long sections of
8" header pipe,
perforated
8" PVC riser pipe
5' min.
Perforated interval
15' x 15' min. sump
(Fill with drain rock)

Figure 5-30. Typical inclined leachate monitoring and removal system.

5.6.6 Covers and Closure of Lined Waste Impoundments

Covers and closure are required for all lined waste impoundments. In addition to protecting the surrounding environment, covers should provide aesthetically pleasing appearance. The subject of covers is presented and discussed in detail in the Technical Resource Document "Evaluating Cover Systems for Solid and Hazardous Materials" (Lutton, 1982), a companion study to this document. The closure of a lined waste impoundment facility involves several components and procedures. This fairly complex operation is described in detail in a companion TRD, "Closure of Hazardous Waste Surface Impoundments" (EPA, 1982).

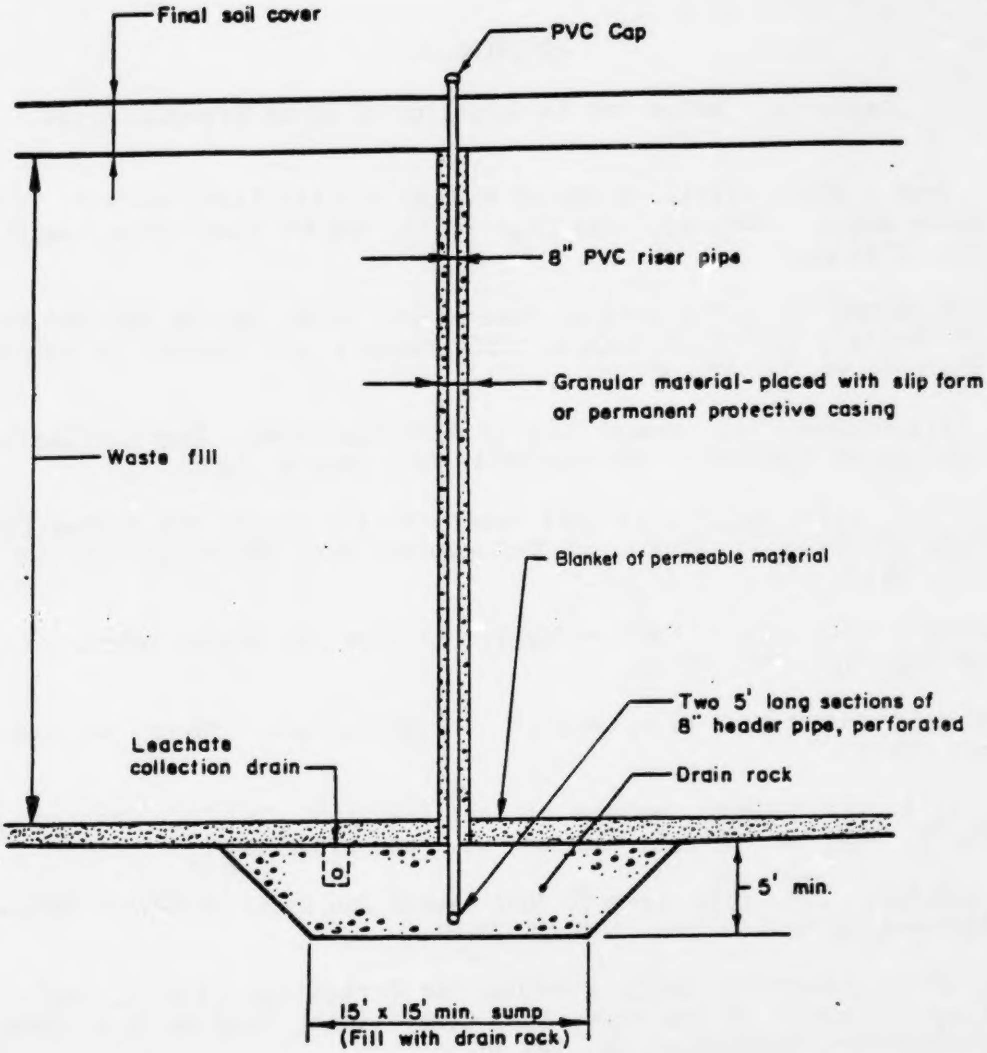

Final soil cover
PVC Cap
8" PVC riser pipe
Granular material- placed with slip form or permanent protective casing
Waste fill
Blanket of permeable material
Two 5' long sections of 8" header pipe, perforated
Leachate collection drain
Drain rock
5' min.
15' x 15' min. sump (Fill with drain rock)

Figure 5-31. Typical vertical leachate monitoring and removal system.

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CHAPTER 6

MANAGEMENT, OPERATIONS, AND MAINTENANCE OF LINED WASTE DISPOSAL FACILITIES

6.1 INTRODUCTION

The proper management of a lined waste disposal facility is important if the performance of the impoundment is to be maintained and the maximum life of the liner and the design criteria are to be realized. Special measures must be taken into account in the management of facilities that are lined. It is necessary:

a. To protect the integrity of the impoundment and of the liner.

b. To monitor the performance of the liner system to determine whether it is operating within the design criteria and is not failing, i.e. monitor the groundwater, the drainage system below the liner, piping, pumps, etc.

c. To monitor the condition of the liner to determine if there are any abnormal swelling, degradation, or changes in properties.

6.2 STANDARD OPERATING PROCEDURES FOR A WASTE DISPOSAL FACILITY

The two basic type of impoundments to be encountered are:

a. Pits, ponds, and lagoons.
b. Solid waste landfills.

The first group of impoundments are all open where the liner may or may not be exposed to the weather. Depending upon the materials and the construction, the liner may be protected by various types of covers. In the case of landfills, the liners will be buried for most of their service lives (see Chapter 5). Several standard handbooks and manuals are available on the operations of such impoundments. (EPA, 1978; ASCE, 1976; EPA, 1973) However, in the case of lined impoundments, additional information should be incorporated in the standard operating procedures manual for the specific disposal facility. The additional requirements and procedures in an operating manual should reflect the specific type of material that was used and construction details. The operating and procedures manual should be prepared by the design, construction, and operations team and should include, as a minimum, the following:

- Operation and maintenance staff requirements and structure.
- Facility description and design parameters.

- Emergency shut-down procedures.
- Operation variables and procedures.
- Facility trouble shooting procedures.
- Preventive maintenance requirements.
- Specialized maintenance procedures.
- Plant personnel safety requirements and procedures.
- Equipment maintenance records.
- Site inspection records
- List of permissible wastes.
- List of unacceptable wastes.
- Master file noting changes such as additions, revisions or deletions to procedures.

6.3 INFORMATION ON DESIGN, CONSTRUCTION, AND MATERIALS OF CONSTRUCTION

Detailed information regarding all of the components of the liner system should be available to the operating personnel. Of particular importance is information on the liner, and information on its characteristics and properties. This information should be obtained from the supplier, manufacturer of the liner, the designer of the site, and the installer. Quality control data and "as-built" drawings and information should also be obtained. Samples of the liner material and other components should be retained for possible use in cases of malfunctioning of the impoundment. A full discussion should be obtained from the supplier as to the limitations of the liner material. The material was selected on the basis of its compatibility with the wastes which it will contain; consequently, deviations in the waste composition from the anticipated composition should be avoided. Information of this type should be incorporated into the operating manual and into the operator training program.

6.4 CONTROL OF INCOMING WASTE

As indicated in the previous section, the composition and character of the waste must be controlled to avoid possible damage to the liner system. It is recognized that a control will be maintained of the hazardous materials that go into the impoundment. However, there is an additional requirement to avoid materials that might be aggressive to the liner. An approximate analysis should be performed on incoming waste to determine the amount of such constituents in the waste. Compatibility of the incoming waste with the wastes in the impoundment should be assured. Generally, there will be some dilution; however, the added waste may have a synergistic and damaging effect upon the liner. The operator should develop a knowledge of the types of industries in the area to be aware of those materials that might be encountered as wastes for the disposal.

Liquids or sludges to be placed in a landfill may be solidified by mixing with soil, a suitable dry absorbent, or by addition of selected chemicals. Drums of liquid hazardous wastes are, in general, not allowed in landfills.

In order to know the contents of the waste impoundment, records should be kept of the wastes being disposed. This, of course, is being done to meet the standard requirements; however, the organic and inorganic constituents that are aggressive toward liners should also be recorded. The waste should be analyzed periodically in order to know its composition. Chemical reactions and volatilization of the constituents within the waste impoundment will probably change the composition of the waste. Adequate means should be incorporated in the design of the impoundment for the addition of wastes. Over-the-edge dumping of wastes should be avoided, as should the addition of hot waste directly on a liner. "Sacrificial" covers have been used on slopes to avoid damage to a liner when wastes have been dumped over the edge. These covers can be replaced when they have deteriorated. Specially designed covers and troughs have also been made for this purpose.

6.5 MONITORING THE PERFORMANCE OF THE IMPOUNDMENT

The principal purpose of the impoundment is to contain a waste and prevent pollutants from leaving the impoundment. Consequently, the principal means of measuring the performance of such an impoundment is to monitor either a drainage system below the liner or the groundwater. These techniques are described in EPA (1977). In addition, the leachate collection system, if leachate is being collected above the liner, should be inspected for the output and composition of the leachate. It is recognized that considerable time may elapse before the generation of leachate.

If a diversion drainage system is set up around the impoundment, this should be inspected periodically to insure that drainage is being diverted.

6.6 MONITORING THE LINER

A system of monitoring the liner should be devised and, if necessary, incorporated in the design of the liner system to observe the condition of the liner itself. The use of coupons at the bottom of a fill or other impoundment has been discussed in Chapter 5. A program of retrieval of these coupons should be set up to cover the operating time of the impoundment before it is closed.

Any damage to a liner that is observed should be repaired as quickly as possible in order to avoid a massive failure. Openings in the liner can cause damage to the earthwork below. The vents should be inspected regularly to avoid plugging.

Impoundments holding wastewater may require cleaning to remove sludges. Care must be taken during cleaning so as not to damage the liner. Cleaning crews should be supervised by someone familiar with the liner to assure that punctures or tears are prevented, or patched if they occur. If sludge is to be removed from the bottom of a wastewater impoundment, some type of nonmechanical means should be used, e.g. a suction hose or dredging head. This should minimize the potential for liner damage.

Following cleaning, the liner should be thoroughly inspected for its condition and possible distress.

6.7 CONDITION OF EARTHWORK

In the case of ponds and lagoons, regular inspections should be made of the embankments and berms. Attention should be given to possible ground movements, cracks, and erosions of the earth. Since an erosion control problem usually exists when earth is exposed on an embankment slope, preventive measures should be taken in the design. However, the inspection is still needed because failure of the earthwork can result in failure of the liner.

6.7.1 Vegetation Control

Growth of vegetation must be controlled around the perimeter of any impoundment. This must be accomplished to prevent damage to the liner from the anchor trench down the side slope. Damage can result if weed growth begins under the liner or, if a soil cover is present, on top of the liner. In the latter case, roots of plants can penetrate the liner creating a potential failure point. Ideally, the berm area around the impoundment should be treated with weed killer initially, and maintained in a weed-free condition.

6.7.2 Rodent Control

Rodents, such as gophers, squirrels, rats, muskrats, and mice, can present severe problems for the owner of a lined impoundment. These animals will attack and possibly damage a liner if the liner blocks their path to food or water. Rodents have also been known to eat PVC material, particularly certain ground squirrels. The presence of these animals at the construction site should be assessed during design. Provisions to control their impact can then be made and incorporated into construction.

6.8 INSPECTION OF APPURTENANCES

Many of the failures of liner systems occur at penetrations of the liner by appurtenances. Whenever possible, these should be inspected on a regular basis to check their integrity and make the needed repairs.

6.9 GENERAL COMMENTS

It is desirable to make on-site inspection of the impoundment on a regular basis and to perform preventive maintenance.

Vandalism and unauthorized dumping of wastes must be carefully monitored. These may be curtailed by having limited vehicular access to the disposal site, locating the site out of general view, and by fencing in ponds and similar impoundments.

Inasmuch as liner technology is relatively new and basic experience is limited, good records should be kept of the performance of the sites. Failures and difficulties should be noted.

6.10 UNACCEPTABLE PRACTICES

Certain operational procedures are not acceptable if the integrity of the lined waste impoundment facility is to be maintained. These procedures include, but are not limited to, the following:

a. The discharge of high-temperature waste liquids onto exposed or unprotected liners, i.e. liners with no soil cover or with insufficient standing liquid levels.

b. The passage of any vehicle over any portion of an exposed liner.

c. The discharge of incompatible wastes to the facility.

d. The direct discharge of wastes with high hydraulic energy upon a liner without adequate provision for energy dissipation.

e. Unauthorized modifications or repairs to the facility.

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CHAPTER 7

COSTS OF LINING MATERIALS FOR WASTE DISPOSAL FACILITIES

Based on known performance information and given the proper design of a facility, it appears that a number of technically suitable materials can be selected for lining a specific disposal facility. Costs, therefore, may be an important factor in the ultimate selection of a lining material. Although the liner is only part of the total construction of such a facility, its cost can be a significant factor in overall costs. Consequently, the costs of liners will be considered by designers and engineers in their selection of a specific material for a waste storage or disposal impoundment.

7.1 GENERAL FACTORS CONTRIBUTING TO THE COSTS OF LININGS

A wide range of factors are involved in the cost of lining materials. Some of these factors are:

- The type of material used. Materials costs are essentially determined by the prices of the raw materials necessary to the manufacture of the liner. An on-site soil, if it is found to be suitable, will probably be the least expensive. A choice between other materials may be made on a cost-benefit basis.

- The location of the facility and the transportation costs involved in bringing the lining material or fill to the site. Liner projects in remote areas with rugged terrain will have higher costs than sites with more favorable topography and geology or located nearer to the source of liner materials.

- As with most construction activities, the time of the year affects labor availability and productivity. In addition, inclement weather can disrupt liner installation. In the case of membrane liners, successful field seaming requires a fairly narrow range of environmental conditions; such liners cannot be placed in excessive heat or cold, snow or rain, or on nonstable or wet ground. Delays in construction and liner placement can thus result. Adverse weather conditions can affect the placement of other liner materials as well.

- The size of the disposal facility can have a significant effect upon the cost per unit area of liner As with most projects and construction materials, the larger the contract, the lower the unit cost of work productivity and materials. Large liner projects usually have significant economies of scale.

- Type of soil on site. Regardless of whether the on-site soil is used as the lining material or as the subgrade for either a liner fabricated on the site or a prefabricated liner, the type and condition of the soil can affect costs. Sand or a soil with a limit on the maximum particle size may be needed as a bedding for membrane liners. A porous soil cover is a necessary part of a landfill liner system. It is needed for leachate drainage and collection and to protect the membrane liner against damage by equipment such as tracked vehicles and compactors that operate above the liners to compact the refuse. However, as all liners for MSW landfills need to be covered, the cost of the soil cover itself will essentially not be affected by the choice of liner.

- The differences in the properties of the lining materials may have a small effect upon the cost of site preparation and installation of liners, particularly in soil compaction and subgrade preparation costs and the need for relatively small particle size bedding on which to place membrane liners. Also, a herbicide may be needed with some liners to prevent puncturing by plant growth under a newly laid membrane.

- Differences in installation costs, such as field seaming of the sheeting or panels into the final liner. Some materials will require more work effort and quality control than others. Final installed costs will take into account these differences, however.

During the past several years, cost data have been developed. They were reviewed in October 1973, updated in 1977, and resurveyed in 1981. Generally, the 1973 and 1977 estimates did not include the costs for site and surface preparation, which are essentially the same for all liner types, nor the costs of the soil cover on the liner needed in landfill construction. The cost estimates for 1980 and 1981 include actual winning bids for liner jobs. Major technological advances have occurred since 1973, as well as large cost increases. The estimates for 1980 and 1981 include subgrade preparation unless otherwise noted.

7.2 POLYMERIC MEMBRANE LINERS

Prices for the membrane liners are quoted in a variety of ways:

- As "rolled goods" or sheeting as produced by liner manufacturers.

- As fabricated liners, e.g. those produced by the factory-seaming of sheeting into large panels which are then sold to installers.

- As final installed costs which involve the assembly of the panels at the site.

Due to the structure of the industry, the prices of some liners are quoted in all three ways. When the liner manufacture, fabrication, and installation are performed by a single company, only a single price may be quoted, i.e. installed costs.

As the polymer membrane industry is a minor segment of the polymer industry, raw material costs are set by producers of polymers and of other ingredients of the liner compound. Because polymer materials, in turn, are made of chemicals from petroleum sources, costs ultimately are dependent upon costs of natural gas or crude oil feedstocks. The price increases of these petroleum commodities resulted in the corresponding rise in polymer costs for membrane production throughout the 1970s. Recent (1980-1982) economic factors have reduced the bid prices for liner projects.

Estimated cost data for polymeric membrane liners are presented in Table 7.1. The unit costs shown cover the period 1973 - 1981 and reflect installed cost only. They do not necessarily represent the total cost of a liner system, as other system components such as groundwater monitoring wells may be required. Also, the costs presented do not reflect equal service life or performance of the liners.

Since 1980, however, several factors have contributed to the moderation of monomer and polymer prices. First, reduced capital expenditures have severely curtailed demand for polymers in many major markets, such as housing, automobiles, commercial construction, packaging, and aerospace, each of which uses hundreds of millions of pounds of these materials. Second, there is a large over-capacity for chemical polymer production which has led to significant discounting from list prices of polymers. These recent trends are not reflected in the cost data presented.

7.3 SOIL, ADMIX, AND SPRAYED-ON LINERS

Cost estimates for soil, admix, and sprayed-on asphalt membrane liners are presented in Table 7.2. The original data were collected in 1973 and updated periodically. The data for 1980 show the most recent update. As with the polymeric membrane liners, the costs shown include neither the costs for site and surface preparation, nor the costs of a soil cover. Specific cost data for these liner types are difficult to obtain and are heavily influenced by geographic location, especially transportation costs.

The costs for asphalt-concrete liners are closely related to those for asphalt paving concrete. Existing equipment and technology are available which can be used as is or with modification to install liners. Thus, liners of soil or admix materials may be cost-effective for lining some waste disposal impoundments, provided they meet the technical requirements.

7.4 CASE STUDY METHODOLOGY FOR ANALYZING COST

To facilitate a deeper understanding of estimating the total cost of lined disposal facilities, the "case study" analysis methodology has been selected as the vehicle for estimating costs and to aid in liner selection. In case study analysis, detailed construction drawings and specifications are neither prepared nor desired. Instead, it is necessary only that a reasonably close approximation of the size, location, type of construction, general layout and costs of various components be developed and that this information be given in sufficient detail to permit comparisons between alternative plans or with established standards. Such a case study is presented in Appendix VI.

TABLE 7.1. COSTS OF FLEXIBLE POLYMERIC MEMBRANE, PLASTIC, AND RUBBER LINERS

Material	Nominal thickness, mils	Fabric reinforcement[a]	1973		1977		1980	1981
			Price, fob $/yd²	Installed cost[b] $/yd²	Delivered cost[c] $/yd²	Installed cost[b] $/yd²	Installed cost[b] $/yd²	Installed cost[b] $/yd²
Butyl rubber	30	no	2.25	3.25-4.00	2.70-3.15	3.40-3.60	...	...
		yes	...	...	2.79-3.24	...	4.10-4.90[d]	...
Chlorinated polyethylene (CPE)	30	no	2.25	2.43-3.24	2.70-3.15	3.10-3.50	...	...
		yes	...	...	2.79-3.24	3.24-3.78	6.17[e,f]	5.80-10.00[g]
Chlorosulfonated polyethylene (CSPE)	30	no	...	...	2.70-3.15	3.10-3.50	...	...
		yes	1.66	2.88-3.06	2.79-3.24	3.24-3.78	4.70-8.50[h,i,j,k]	5.80-10.00[g]
Elasticized poly-olefin (ELPO)	20	no	...	...	1.80	2.07-2.25	...	...
Ethylene propylene rubber (EPDM)								
covered	30	yes	2.00[l]	2.43-3.42	2.70	3.42-3.50	...	...
uncovered	30	yes	...	...	2.16	2.88	4.10-4.90[d]	...
Neoprene (CR)	30	no	2.07	4.41-5.40	...	...	...	...
		yes	...	...	5.00	5.85-6.75	...	...
Polyethylene								
Low-density (LDPE)	10	no	0.36	0.90-1.44	0.60-0.70	1.10-1.40[m]	...	...
High-density (HDPE)	60	no	...	...	...	...	...	6.75[n]
	80	no	...	...	...	...	...	7.20-7.65[o]
Polyvinyl chloride (PVC)	20	no	.90	1.17-2.16	1.11-1.53	1.44-1.98	...	...
	30	no	1.33	...	1.44-1.89	1.80-2.45	...	...

[a] Fabric reinforcement, usually nylon or polyester scrim.

[b] Installed cost is highly dependent on area being lined.

[c] Delivered cost in dollars per square yard; cost of sheeting in panel - 5000 to 150,000 sq. ft.

[d] Installed cost estimate. Key Enterprises for April 1978, 45 mil nylon reinforced.

[e] 45 mil thickness, three ply, one ply polyester scrim.

[f] Engineering News Record, July 10, 1980, p. 61; does not include subgrade preparation on soil cover.

[g] StaFlex Corporation estimate, May 1981, for 30, 36, and 45 mil reinforced CPE and CSPE.

[h] 45 mil thickness, five ply, two ply polyester scrim.

[i] Winning bid, June 11, 1980, City of Seattle, North Beacon Reservoir Reline.

[j] Installed cost Candelaria Silver Project, 30 mil 8 x 8 scrim, $4.70 per square yard, August 1980.

[k] Installed cost Mart[illegible] Marietta Aluminum Co., 30 mil 8 x 8 scrim, $4.75 per square yard, July 1980.

[l] The cost over the range of area of 150,000-500,000 sq ft is usually in the range of $0.05-0.06 per square foot.

Soil cover: Source 1 - $0.10-.50/yd²/foot of depth
Source 2 - 0.05-.07/ft²/foot of depth

[m] If tape is used, tape cost: $0.05-.06/linear foot.

[n] Rubber and Plastics News II, August 24, 1981, for 60 mil thickness.

[o] StaFlex Corporation estimate, May 5, 1981, high-density polyethylene, 80 mil thickness unreinforced.

TABLE 7.2. COST ESTIMATES OF SOIL, ADMIX, AND ASPHALT MEMBRANE LINERS

Liner type	Installed Cost Dollars per square yard 1973[a,b]	1980
Soil + bentonite 9 lb/sq yd (1 psf)	$0.72	$1.31[c]
Soil cement 6-in. thick + sealer (2 coats - each 0.25 gal/sq yd)	1.25	2.27[c]
Soil asphalt 6-in. thick + sealer (2 coats - each 0.25 gal/sq yd)	1.25	2.27[c]
Asphalt concrete, dense-graded paving with sealer coat (hot mix, 4-in thick)	2.35 - 3.25	5.00 - 7.00[c]
Asphalt concrete, hydraulic (hot mix, 4 in thick)	3.00 - 4.20	5.46 - 7.64[c]
Bituminous seal (catalytically blown asphalt) 1 gal/sq yd	1.50 - 2.00 (with earth cover)	2.73 - 3.64[c]
Asphalt emulsion on mat (polypropylene mat sprayed with asphalt emulsion)	1.26 - 1.87	1.87 - 3.40[c]

[a] Haxo, 1976 (October, 1973 costs).

[b] Estimated installed costs on west coast.

[c] Costs updated based on Engineering News Record data. Materials cost index for October 1973 was 788.5. Materials cost index for November 1980 was 1433.7.

CHAPTER 8

SELECTION OF A LINER MATERIAL FOR A WASTE DISPOSAL FACILITY

8.1 INTRODUCTION

The designer of a lined waste disposal facility is faced with making the selection of a liner or liners which meet a wide range of requirements. This chapter summarizes the approach that could be taken making that selection.

It is assumed that a basic decision has been made as to the site for the waste disposal facility; however, there are factors in the soil and geology of the site which must be known before the site selection can be made. Obviously, the soil and geology at one site would be preferable to another from the standpoint of impoundment requirements. In making a decision regarding the selection, it is necessary to consider the liner as a part of a many-layered system of different permeabilities and characteristics. These layers extend from the waste itself and the waste fluid through the liner and subgrade, the soil base and finally the aquifer. The principal factors can be enumerated as follows:

- Type of waste and composition.
- Required operating life of disposal facility.
- Required life of the liner after closure of the facility.
- Soils on or nearby site, including subsoil.
- Hydrology and groundwater.
- Significant environmental factors.
- Acceptable flow out of impoundment.
- Permeability of available clay soil.
- Review of available materials which appear to be potentially compatible.
- Compatibility tests of specific materials with sample of the waste to be contained.
- Costs of principal candidate material and installation.

- Reliability of materials, seams, joints, etc. and documented experience in the technology.

8.2 THE FUNCTION OF THE WASTE DISPOSAL FACILITY

The first thing that must be known is the type of waste that is to be contained, whether it be a solid, liquid, sludge, etc. The type of waste will determine the general type of disposal site. Solid waste generally will go into landfills, and liquid or partially liquid waste will be impounded in ponds or lagoons. The character of the waste itself should be known as to its chemical composition and whether there are components present that are highly aggressive to the various types of lining materials.

The designer should know the anticipated life required of the impoundment. A landfill liner should last for extended periods of time. Many impoundments are either evaporating or holding ponds which may require only relatively short periods of service. The selection of a liner can be greatly affected by the anticipated required service life.

Superimposed on these factors is the basic performance requirement that will be imposed by the various regulatory agencies. Together, these will form a minimum performance requirement for the site.

8.3 CLAY SOIL ON SITE

It is important to know whether the soil on-site, or soil available from a borrow pit nearby, can be used as a liner, or whether it should be used as a subgrade for other types of lining materials. From the cost standpoint, soils are generally the least expensive, but they have a variety of limitations.

In making the decision as to the suitability for the liner, the permeability to water and to the waste fluid should be determined. Tests should be made as to the structural strength of the soil. If the soil does not have adequate permeability or is sensitive to the waste, it still must be tested to determine its quality as a subgrade, where strength is a major factor.

8.4 HYDROLOGY

The groundwater level is an important factor in the siting of a waste disposal facility, but it also should be evaluated and determined as a part of the liner selection process as should the permeability of the in-place soil below the facility. The permeability of the native soil and its thickness can have a significant bearing on the design of the soil liner, as discussed in Chapter 5 and Appendix VII. The flow of water within the aquifer also can be a factor in the total system as there can be a dilution of any pollutant species that might enter the aquifer.

8.5 SIGNIFICANT ENVIRONMENTAL FACTORS

The significant environmental factors include such items as prevailing winds, temperature, rainfall, drainage, and the subsurface geology. It is important to know the overall geological character of the rocks, soil, depth of strata, and the chemical and physical characteristics of the subgrade soils, clays, and rocks.

8.6 ACCEPTABLE FLOW THROUGH A LINER

Once the permeabilities have been obtained for the various layers that make up the impoundment system from waste to groundwater, one can calculate the thickness of a liner of a given permeability to meet the basic flow requirements. It is possible, in making this calculation, that the specific soils which were expected to be used will require too great a thickness to be compacted properly. At this point, the decision may be that other lining materials must be used.

8.7 REVIEW OF AVAILABLE MATERIALS

With the knowledge of the waste that will be impounded and the level of permeability required in the liner, a review should be made of those materials which appear potentially suitable as liners. A screening of these materials can be made based upon the state-of-the-art knowledge and a selection made of those which are potentially compatible with the waste fluid. Information in this Manual and some of the references should be useful. Also, guidance can be obtained from suppliers of lining materials.

8.8 COST OF LINER MATERIALS

A preliminary estimate can be made of the costs of the various lining materials such as found in Chapter 7. It is anticipated that several lining materials may be suitable for the lining of the specific site and the selection can be based upon costs and other considerations.

8.9 COMPATIBILITY TESTS

The principal candidates for the liner should be subjected to exposure tests in direct contact with the waste. Compatibility tests for soils and membranes are suggested in Appendix III. These tests should indicate the compatibility of the liner to long exposure with the wastes. Completely incompatible combinations become obvious in relatively short times. However, due to low concentration of aggressive constituents in a waste liquid, incompatibility of some combinations may take months or even years to show up. At the present state-of-the-art, extended lives of many years have not been demonstrated in actual service in waste disposal facilities; dependence must be placed on accelerated testing to assess compatiblity and durability such as immersion tests at room temperature and 50°C.

8.10 SELECTION OF LINER MATERIAL

In making the final selection of a liner material, some factors take precedence over others. The principal function of the liner is to impede the flow of pollutants from the impoundment for the duration of its required life and sometimes to form the barrier table on which the flow of a leachate can take place for collection and treatment.

Although there may be some variation in the priority of the factors, the following requirements must be met:

a. Compatibility and durability of the liner in the presence of the fluid to be contained.

b. Low permeability to the waste over extended periods of time.

c. Reliability and low risk of failure.

d. Relative ease of installation, quality control, repair, and maintenance.

The selection can also depend on cost if the above requirements are all met. Following the liner selection, the designer can proceed with the detailed design of the disposal facility as it relates to the liner. It is recognized that more than one material may be selected in which case some alternatives may have to be incorporated in the drawings and specifications.

CHAPTER 9

SPECIFICATION FOR CONSTRUCTION OF LINED WASTE IMPOUNDMENTS

9.1 INTRODUCTION

After selecting the liner material and incorporating it into the design of the waste disposal facility, the architect-designer-engineer must prepare the necessary specifications and drawings for the bid package and for use in the construction of the facility.

As in all engineering projects, the preparation of good specifications is essential to obtaining satisfactory construction or to meeting the goals of the project (Goldbloom and White, 1976). Incomplete drawings and specifications can result in high-price bids, construction uncertainties, and inadequate product and performance. It is not possible to prepare adequate performance specifications on a product such as a waste impoundment. Too many uncertainties exist with respect to the performance of different materials and long periods of time are required to demonstrate effective performance. As a consequence, the specifications must be based upon accepted procedures of construction, required values of the properties of the materials used in the project, and quality control at all stages of construction.

9.2 SPECIFICATIONS FOR CONSTRUCTION

Following the procedures set forth in the specification should increase the probability of meeting the project requirements and assuring an effective waste disposal facility. These specifications should include specific instructions for the following:

- Site preparation, embankment, and other earthwork.
- Subgrade preparation.
- Drainage and gas venting systems.
- Appurtenances and penetrations.
- Liner construction for soils, admixes, sprayed-on materials.
- Liner installation, particularly field seaming.
- Quality control by the construction and installation contractors.
- Quality assurance by the owner or his representative.

Construction details are presented in Chapter 5. Table 9-1 lists references which give examples of detailed procedures of the construction, various types of liners, and includes subgrade earthwork and subgrade preparation.

TABLE 9-1. CONSTRUCTION PROCEDURES AND SPECIFICATION FOR LINERS OF WASTE DISPOSAL FACILITIES

Preliminary[a] List of Suggested References

Material	Installation of liner	Subgrade and earthwork
Clay soil	Bureau of Reclamation, 1974, p. 189; Bureau of Reclamation, 1977, pp. 669-700.	Day, 1970, pp. 46-57; Bureau of Reclamation, 1974, pp. 176-184.
Admixes		
Asphalt concrete	Day, 1970, pp. 52-60; Asphalt Inst., 1976, pp. 13-18; Asphalt Inst., 1975, 60 pp.	Day, 1970, pp. 46-47 Asphalt Inst., 1976, pp. 8-9.
Soil cement	Day, 1970, pp. 60-64, PCA, 1979.	Day, 1970, pp. 46-47.
Bentonite-soil	Day, 1970, pp. 64-66 American Colloid Co. and Dowell trade literature.	Day, 1970, pp. 46-47 American Colloid Co. and Dowell trade literature.
Soil asphalt	Day, 1970, pp. 64-66.	Day, 1970, pp. 46-47.
Portland cement concrete	Kays, 1977, pp. 124-131.	
Flexible membranes	Water and Power Resources Service[b], 1980, pp. 4-1 to 4-9; Day, 1970, pp. 47 to 50; Appendix IX; Small, 1980; Morrison et al, 1982; manufacturers and suppliers trade literature.	Water and Power Resources Service[b], 1980, pp. 3-4 to 3-6; Day, 1979, pp. 46-47. Small, 1980; Morrison et al, 1982; manufacturers and suppliers trade literature.
Spray-on membranes		
Asphalt	Asphalt Inst., 1976, pp. 19-20; Day, 1970, pp. 50-51.	
Modified asphalt	Chevron USA, 1978, pp. 7-9 and 13-15; Chevron USA, 1980, pp. 1-9.	
Airblown concrete (shotcrete)	Kays, 1977, pp. 131-136	

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[a] To be expanded in revisions.
[b] Name of the Bureau of Reclamation from November 1979 to May 1981.

9.3 SPECIFICATIONS FOR LINER MATERIALS

In addition to the construction specifications, the liner materials must be controlled and tightly specified. The properties of the various lining materials are described in Chapter 3 and their installation is described in Chapter 5.

The range of materials that fall under the category of polymeric materials, as indicated in Chapter 3, is extensive and the technology is relatively new. Specifications have been developed by polymer manufacturers, sheeting and film manufacturers, and panel fabricators. The specifications thus have emerged from the rubber, plastics, and textile techologies and have varied considerably in requirements and in test methods. Although several test methods may be used to assess the same property, e.g. tear strength, the shape of the test specimens, rates of test, and temperatures of test can vary.

At the present time, the number of generally accepted specifications for lining materials is limited and those that are available are incomplete and inadequate for use in the selection of liners for waste impoundments from currently available materials. The liner industry has a variety of specifications; each company has its own specifications and selected test methods for its specific materials.

9.3.1. Current ASTM Specifications

Five ASTM specifications now exist for lining of canals, ponds, and reservoirs, four of which pertain to polymeric membranes. These five specifications are primarily designed for water impoundment and conveyance. They cover the following materials:

1. Flexible poly(vinyl chloride) sheeting (D3083-76, reapproved 1980).
2. Low-density polyethylene and ethylene copolymer plastic sheeting (D3020-75, reapproved 1980).
3. Vulcanized butyl rubber, neoprene, and ethylene-propylene rubber sheeting (D3253-81).
4. Fabric-reinforced vulcanized butyl rubber, neoprene, and ethylene propylene rubber sheetings (D3254-81).
5. Prefabricated asphalt panels (D2643-80).

The above specifications for the polymeric sheetings state in the scope of each that test methods and standards should be used "to characterize the sheetings and are intended to insure good workmanship and quality. They are not necessarily adequate for design purposes in view of the important environmental factors and specific performance objectives" (ASTM, 1982). They state further that "tests have been selected with aqueous systems and combinations of aqueous and hydrocarbon systems in mind. Other tests may be necessary to establish chemical resistance and durability under the conditions of a particular application".

The specific test methods included in the four specifications for polymeric membrane liners can be grouped into the following categories:

- Tests for analytical properties and information regarding construction and dimensions.
- Tests of the physical properties of unexposed sheetings.
- Tests for environmental and aging effects on the physical properties of sheetings.

The test methods for a given property can differ considerably among the various membranes because of differences in material type, composition, and construction. Table 9-2 shows the specific ASTM test methods that are used in the ASTM specifications for flexible polymeric membranes. Table 9-3 presents the physical requirements for each of the flexible membrane liners in the ASTM specifications. The materials are classified as to whether they are fabric-reinforced or thermoplastic, crosslinked, or crystalline materials without fabric reinforcement. As can be seen from these two tables, some properties are not measured on all materials. Tests for environmental effects and accelerated aging are limited principally with respect to exposure time, e.g. the oven aging test is only run for seven days, the ozone test for seven days, and the soil burial test for 30 days. No test is included for compatibility of candidate liner materials with the waste to be contained. As indicated above, these tests are not adequate for the selection of materials for lining waste impoundments although, in most cases, they were adequate for water impoundment and conveyance applications.

The specifications are limited in scope of the materials that they cover and in some of the properties that are tested. They do, however, give an indication of the amount of sampling that is required, although it appears to be inadequate for small jobs. These specifications do not cover a wide range of materials that are being manufactured and are being used in the lining of waste storage and disposal impoundments. Those not covered in the ASTM specification include membranes of chlorinated polyethylene, chlorosulfonated polyethylene, epichlorohydrin rubber, high-density polyethylene and the various fabric-reinforced thermoplastic sheetings. Among the significant properties that are not included in the test plan are peel tests of adhesion of seams and tensile properties at somewhat elevated temperatures, and puncture tests. They set no requirements for the seams prepared in the field during installation. Requirements regarding such properties are desirable in specifications.

9.3.2 Standards Under Development for Flexible Polymeric Membranes

The American Society of Agricultural Engineers has also developed a specification for flexible membrane linings (ASAE EP 340.1, Installation of Flexible Membrane Linings) for ponds, reservoirs, and canals. This specification covers unreinforced butyl rubber/EPDM, fabric reinforced butyl rubber, polyethylene (low density), and PVC sheeting.

Several other standard-setting organizations have prepared or are preparing specifications on polymeric lining materials, including:

American Society of Civil Engineers (ASCE).
American Water Works Association (AWWA).

TABLE 9-2. PROPERTIES AND ASTM TEST METHODS USED IN ASTM MEMBRANE LINING SPECIFICATIONS[a]

Type of membrane	Membrane without fabric reinforcement			Fabric reinforced
Type of composition[b]	TP	XL	CX	XL
Major polymer in compound[c]	PVC	IIR, EPDM, CR	LDPE	IIR, EPDM, CR
ASTM specification of lining	D3083	D3253	D3020	D3254
Analytical properties, construction, and dimensions				
Thickness	D374	D412	D374/Method C	D751
Polymer composition	D1755	-	-	-
Ash content	-	-	D1278	-
Water extractables	D1239	-	-	-
Plasticizer volatility (activated carbon)	D1203	na	na	na
Physical properties				
Nomenclature	-	D1418	-	D1418
Conditioning	D618	(d)	D618	(d)
Tensile properties				
Tensile strength	D882/Method A	D412	D882/Method A	D751(Grab)
Elongation at break	D882/Method A	D412	D882/Method A	D751(Grab)
Stress at 300% elongation	-	D412	-	-
Strength of factory seams	D3083/Sec. 9.3 D882/Method A	D3253/Sec.7.2	-	D3254/Sec. 7.2
Tear resistance	D1004/D1922[e]	D624	D1922	D751(tongue tear)
Hardness, Duro A	-	D2240	-	-
Compression set	-	D395	-	-
Hydrostatic resistance	-	-	-	D751/Method A
Impact resistance	-	-	D1709/Method B	-
Luminous transmittance	-	-	D2103	-
Pinholes and cracks	D3083	-	D3020	-
Permeability properties	none	none	none	none
Environmental and aging effects				
Blocking	D1146	na	na	na
Dimensional change in heating	D1204	D1204	-	D1204
Brittleness temperature	D1790	D746	-	FTMS-191-5874[f]
Effect of liquids				
Water resistance	-	D471	-	D471
Oil resistance (if required)	-	D471	-	D471
Air oven aging	-	D573	-	D573
Ozone resistance at 40°C and in 50 pphm O_3	-	D1149 (strip specimen at 20% elongation)	-	D518/Mtd B (looped specimens) D1149
Flame resistance (if required)	-	C542	-	C542
Soil burial	D3083	-	-	-
Tensile strength change	D882	-	-	-
Elongation loss	D882	-	-	-

[a] For ponds, canals, and reservoirs.

[b] Type of polymeric composition: TP = thermoplastic, XL = vulcanized, CX = partially crystalline.

[c] Major polymeric compound: PVC = poly(vinyl chloride), IIR = butyl, EPDM = ethylene propylene rubber, CR = neoprene, LDPE = low density polyethylene.

[d] In accordance with individual test method in the column.

[e] Use D1922 for film 8-16 mils and D1004 for sheeting 16-30 mils.

[f] Federal Test Method Standard.

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TABLE 9-3. PHYSICAL REQUIREMENTS IN THE ASTM SPECIFICATIONS FOR FLEXIBLE MEMBRANE LININGS^a

Type of membrane	Membrane without fabric reinforcement					Fabric reinforced membrane		
ASTM specification of lining	D3083-76	D3253-81			D3020-75	D3254-81		
Type of composition^b	TP	XL			CX	XL		
Major polymer in compound^c	PVC^d	IIR	EPDM	CR	LDPE	IIR	EPDM	CR
Analytical properties, construction, and dimensions								
Thickness (nominal), mils	16-30	30	30	30	8-12	32	32	32
Tolerance in % of specified thickness	±7	+15,-10	+15,-10	+15,-10	-	+15,-10	+15,-10	+15,-10
Ash content, % (max)	-	-	-	-	0.5	-	-	-
Water extractables, % (max)	0.35	-	-	-	-	-	-	-
Plasticizer volatility, % (max) (activated carbon)	1.0	-	-	-	-	-	-	-
Physical properties								
Tensile properties								
Tensile strength, psi (min)	2000	1200	1300	1500	1800	95^e	95^e	95^e
Elongation at break, % (min)	250	300	300	250	500	35^f	35^f	35^f
Stress at 300% elongation, psi (min)	-	600	900	-	-	-	-	-
Strength of factory seams, % of breaking strength (min)	80 (in shear)	In shear test, failure should take place in membrane.			-	After one day immersion in distilled water at 22°C, in shear test, failure should be in membrane with no delamination.		
Tear resistance, lbf/in (min)	200	125	125	120	80^g	10^h	10^h	10^h
Hardness, Duro A	-	60±10	60±10	60±10	-	-	-	-
Hydrostatic resistance, psi (min)	-	-	-	-	-	180^i	180^i	180^i
Impact, gf (min avg)	-	-	-	-	45	-	-	-
Luminous transmittance, % (max)	-				1.0			
Pinholes and cracks per 10 yd^2 (max)	1	-	-	-	0	-	-	-
Environmental and aging effects								
Blocking	None	-	-	-	-	-	-	-
Dimensional change on heating, % (max)	5.0^j	$±2.0^k$	$±2.0^k$	$±2.0^k$	-	$±2^k$	$±2^k$	$±2^k$
Brittleness temperature, °C	-29±0.5 Not more than 2 out of 10 will fail	-40	-54	-34.5	-	-40 No cracks	-40 No cracks	-40 No cracks
Permanent set after 22 h at 70°C, % (max)	-	-	-	40	-	-	-	-
Effect of liquids								
Water resistance, weight change at 1 week at 70°C in water, % (max)	-	±1	±1	±10	-	-	-	-
Oil resistance, % (max)^l	-	-	-	80	-	-	-	80
Air oven aging^k								
Tensile, % retention of original (min)	-	60	70	80^m	-	85,	85,	85,
Elongation, % retention of original (min)	-	60	50	60^m	-	35^f	35^f	35^f
Hardness, max change in points (Duro A)	-	-	-	$±10^m$		-		-
Ozone resistance at 1 week, at 40°C and in 50 pphm O_3, other conditions	-	20% strain No cracks	-	20% strain 100 pphm O_3 No cracks	-	Looped test specimens exposed 7 d No cracks	After air oven aging^k No cracks	No cracks
Soil burial, days	30	-	-	-	-	-	-	-
Tensile strength change, % (max)	±5.0	-	-	-	-	-	-	-
Elongation loss, % (max)	20.0	-	-	-	-	-	-	-

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[a] For ponds, canals, and reservoirs. Samples shall be selected at random from each 10,000 yd^2 of material

[b] Type of polymeric composition: TP = thermoplastic, XL = vulcanized, CX = partially crystalline.

[c] Major polymeric compound: PVC = poly(vinyl chloride), IIR = butyl, EDPM = ethylene propylene rubber, CR = neoprene, LDPE = low density polyethylene.

[d] Formulated from homopolymer vinyl chloride resin of type GP in accordance with specification D1755.

[e] Minimum breaking strength in both directions in pounds force.

[f] Maximum percent elongation in both directions.

[g] Grams force per mil.

[h] Pounds force. For thicknesses other than 32mils, the tear requirements in the warp direction: 20 mil, 5 lbf; 45 mil and 62 mil, 12 lbf; in the fill direction, 20 mils, 5 lbf; 45 and 62 mil, 10 lbf.

[i] For other thicknesses the minimum requirements for hydrostatic resistance: 20 mils, 100 psi; 45 mils and 60 mils, 190 psi.

[j] Heat at 79°C for 24 hours.

[k] Air oven aging for 7 d at 115°C.

[l] Change in volume after 70 h at 100°C in ASTM No. 3 oil.

[m] Air oven aging 70 h at 100°C.

National Sanitation Foundation (NSF).
U. S. Bureau of Reclamation (USBR).

Recently the National Sanitation Foundation and the liner industry have undertaken to prepare general standards. All segments of the industry, including raw materials producers, membrane manufacturers, fabricators, installers, and design engineers are participating in developing concensus standards. At present (October 1982), final agreement with respect to the specific materials and their manufacturing requirements and properties has not been achieved.

9.3.3 Suggested Standards for Representative Flexible Polymeric Membranes

In view of the lack of accepted standards to cover currently available flexible membrane materials for lining waste disposal impoundments, suggested standards for representative membranes currently available (October 1982) are presented in Appendix VIII using currently available data. They are based largely on the properties and tests listed in Table 3-7 in Chapter 3 and reflect some of the current efforts to develop standards. The required values are preliminary and subject to change.

These specifications should not be used to select materials. Selection, as indicated in Chapter 8, should be based upon factors of compatibility with the waste liquid, durability, etc. These specifications should be used as a means of assuring the quality of the lining material that is installed in the waste disposal facility and of assuring that the quality of the material is the same as was observed in the compatibility tests. Not all tests are used for quality control, e.g. burial exposure test, but instead set the requirements for the quality of the selected material. For quality control purposes, it is suggested that random samples be taken from each 10,000 square yards of sheeting; however, a minimum of five samples for quality control testing should be taken from each job. Each sample should be three by six feet and should include a factory seam if the membrane requires factory fabrication.

These standards present values for different properties which can characterize membranes currently on the market. By themselves, they are not adequate to predict product performance, and cannot be used for engineering design purposes. For example, the low temperature resistance numbers represent qualities measured after a few minutes exposure at a given temperature and should not be interpreted or extrapolated into installation temperatures and conditions. Correlations of specific properties and tests with field performance of lining materials have not been established but the results of the tests indicate the quality of the specific material under test.

As in the case of the ASTM specifications, requirements have not been set for several important properties because of the lack of data at this time. Of particular importance are requirements relating to peel adhesion of seams, puncture resistance and complete test properties of fabric-reinforced membranes.

The industry is developing new materials and new products which, in the future, the designer and engineer will be able to incorporate into their designs for lined disposal facilities. As these materials are developed, specifications will be set for use in impoundment construction and quality control. They will be incorporated in future revisions of this Technical Resource Document.

REFERENCES

Chapter 9 - Specifications for Construction of Lined Waste Impoundments

The Asphalt Institute. 1975. Model Construction Specifications for Asphalt Concrete and Other Plant-Mix Types. 5th ed. (SS-1). College Park, MD. 60 pp.

The Asphalt Institute. 1976. Asphalt in Hydraulics. (MS-12). College Park, MD. 65 pp.

ASTM Standards. 1982. Part 15. American Society for Testing and Materials, Philadelphia, PA:

D2643-80	Standard Specification for Prefabricated Asphalt Reservoir Pond, Canal, and Ditch Liner (Exposed Type).
D3020-75	(Reapproved 1980) - Standard Specification for Polyethylene and Ethylene Copolymer Plastic Sheeting for Pond, Canal, and Reservoir Lining.
D3083-76	(Reapproved 1980) - Flexible Poly (vinyl chloride) Plastic Sheeting for Pond, Canal, and Reservoir Lining.
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Day, M.E. 1970. Brine Disposal Pond Manual. Office of Solid Waste Contract No. 14-001-1306. Bureau of Reclamation, U.S. Department of the Interior, Denver, CO. 134 pp.

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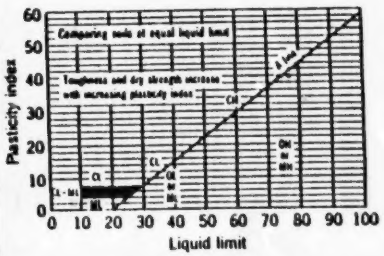
Note: From November 1979 to May 1981, the Bureau of Reclamation was known as the Water and Power Resources Services.

APPENDIX I
UNIFIED SOIL CLASSIFICATION SYSTEM

Field Identification Procedures (Excluding particles larger than 75mm and basing fractions on estimated weights)						Group Symbols [a]	Typical Names	Information Required for Describing Soils		Laboratory Classification Criteria
Coarse-grained soils More than half of material is *larger* than 75 µm sieve size[b] (The 75 µm sieve size is about the smallest particle visible to naked eye)	Gravels More than half of coarse fraction is larger than 4.75mm sieve size	Clean gravels (little or no fines)	Wide range in grain size and substantial amounts of all intermediate particle sizes			*GW*	Well graded gravels, gravel-sand mixtures, little or no fines	Give typical name; indicate approximate percentages of sand and gravel, maximum size; angularity, surface condition, and hardness of the coarse grains; local or geologic name and other pertinent descriptive information; and symbols in parentheses For undisturbed soils add information on stratification, degree of compactness, cementation, moisture conditions and drainage characteristics Example: *Silty sand*, gravelly, about 20% hard, angular gravel particles 12 mm maximum size; rounded and subangular sand grains coarse to fine, about 15% non-plastic fines with low dry strength, well compacted and moist in place, alluvial sand, (*SM*)	Use grain size curve in identifying the fractions as given under field identification	Determine percentages of gravel and sand from grain size curve. Depending on percentage of fines (fraction smaller than 75 µm sieve size) coarse grained soils are classified as follows: Less than 5% *GW, GP, SW, SP* More than 12% *GM, GC, SM, SC* 5% to 12% *Borderline* cases requiring use of dual symbols $C_U = \frac{D_{60}}{D_{10}}$ Greater than 4 $C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3
			Predominantly one size or a range of sizes with some intermediate sizes missing			*GP*	Poorly graded gravels, gravel-sand mixtures, little or no fines			Not meeting all gradation requirements for *GW*
		Gravels with fines (appreciable amount of fines)	Nonplastic fines (for identification procedures see *ML* below)			*GM*	Silty gravels, poorly graded gravel-sand-silt mixtures			Atterberg limits below "A" line, or *PI* less than 4 Above "A" line with *PI* between 4 and 7 are *borderline* cases requiring use of dual symbols
			Plastic fines (for identification procedures, see *CL* below)			*GC*	Clayey gravels, poorly graded gravel-sand-clay mixtures			Atterberg limits above "A" line, with *PI* greater than 7
	Sands More than half of coarse fraction is smaller than 4.75mm sieve size	Clean sands (little or no fines)	Wide range in grain sizes and substantial amounts of all intermediate particle sizes			*SW*	Well graded sands, gravelly sands, little or no fines			$C_U = \frac{D_{60}}{D_{10}}$ Greater than 6 $C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3
			Predominantly one size or a range of sizes with some intermediate sizes missing			*SP*	Poorly graded sands, gravelly sands, little or no fines			Not meeting all gradation requirements for *SW*
		Sands with fines (appreciable amount of fines)	Nonplastic fines (for identification procedures, see *ML* below)			*SM*	Silty sands, poorly graded sand-silt mixtures			Atterberg limits below "A" line or *PI* less than 5 Above "A" line with *PI* between 4 and 7 are *borderline* cases requiring use of dual symbols
			Plastic fines (for identification procedures, see *CL* below)			*SC*	Clayey sands, poorly graded sand-clay mixtures			Atterberg limits below "A" line with *PI* greater than 7
	Identification Procedures on Fraction Smaller than 380 µm Sieve Size *									
Fine-grained soils More than half of material is *smaller* than 75 µm sieve size			Dry Strength (crushing characteristics)	Dilatancy (reaction to shaking)	Toughness (consistency near plastic limit)					
	Silts and clays liquid limit less than 50		None to slight	Quick to slow	None	*ML*	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity	Give typical name; indicate degree and character of plasticity, amount and maximum size of coarse grains; colour in wet condition, odour if any, local or geologic name, and other pertinent descriptive information, and symbol in parentheses For undisturbed soils add information on structure, stratification, consistency in undisturbed and remoulded states, moisture and drainage conditions Example: *Clayey silt*, brown; slightly plastic; small percentage of fine sand; numerous vertical root holes; firm and dry in place; loess; (*ML*)		 Plasticity chart for laboratory classification of fine grained soils
			Medium to high	None to very slow	Medium	*CL*	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays			
			Slight to medium	Slow	Slight	*OL*	Organic silts and organic silt-clays of low plasticity			
	Silts and clays liquid limit greater than 50		Slight to medium	Slow to none	Slight to medium	*MH*	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts			
			High to very high	None	High	*CH*	Inorganic clays of high plasticity, fat clays			
			Medium to high	None to very slow	Slight to medium	*OH*	Organic clays of medium to high plasticity			
Highly Organic Soils			Readily identified by colour, odour, spongy feel and frequently by fibrous texture			*Pt*	Peat and other highly organic soils			

From Wagner, 1957.

[a] *Boundary classifications*. Soils possessing characteristics of two groups are designated by combinations of group symbols. For example *GW-GC*, well graded gravel-sand mixture with clay binder.

[b] All sieve sizes on this chart are U.S. standard.

Field Identification Procedure for Fine Grained Soils or Fractions

These procedures are to be performed on the minus 380 µm* sieve size particles. For field classification purposes, screening is not intended, simply remove by hand the coarse particles that interfere with the tests.

Dilatancy (Reaction to shaking): *

After removing particles larger than 380 µm sieve size, prepare a pat of moist soil with a volume of about 8000 mm³. Add enough water if necessary to make the soil soft but not sticky.

Place the pat in the open palm of one hand and shake horizontally, striking vigorously against the other hand several times. A positive reaction consists of the appearance of water on the surface of the pat which changes to a livery consistency and becomes glossy. When the sample is squeezed between the fingers, the water and gloss disappear from the surface, the pat stiffens and finally it cracks or crumbles. The rapidity of appearance of water during shaking and of its disappearance during squeezing assist in identifying the character of the fines in a soil.

Very fine clean sands give the quickest and most distinct reaction whereas a plastic clay has no reaction. Inorganic silts, such as a typical rock flour, show a moderately quick reaction.

Dry Strength (Crushing characteristics): *

After removing particles larger than 380 µm sieve size, mould a pat of soil to the consistency of putty, adding water if necessary. Allow the pat to dry completely by oven, sun or air drying, and then test its strength by breaking and crumbling between the fingers. This strength is a measure of the character and quantity of the colloidal fraction contained in the soil. The dry strength increases with increasing plasticity.

High dry strength is characteristic for clays of the CH group. A typical inorganic silt possesses only very slight dry strength. Silty fine sands and silts have about the same slight dry strength, but can be distinguished by the feel when powdering the dried specimen. Fine sand feels gritty whereas a typical silt has the smooth feel of flour.

Toughness (Consistency near plastic limit): *

After removing particles larger than the 380 µm sieve size, a specimen of soil about 12 mm cube in size, is moulded to the consistency of putty. If too dry, water must be added and if sticky, the specimen should be spread out in a thin layer and allowed to lose some moisture by evaporation. Then the specimen is rolled out by hand on a smooth surface or between the palms into a thread about 3 mm in diameter. The thread is then folded and re-rolled repeatedly. During this manipulation the moisture content is gradually reduced and the specimen stiffens, finally loses its plasticity, and crumbles when the plastic limit is reached.

After the thread crumbles, the pieces should be lumped together and a slight kneading action continued until the lump crumbles.

The tougher the thread near the plastic limit and the stiffer the lump when it finally crumbles, the more potent is the colloidal clay fraction in the soil. Weakness of the thread at the plastic limit and quick loss of coherence of the lump below the plastic limit indicate either inorganic clay of low plasticity, or materials such as kaolin-type clays and organic clays which occur below the A-line.

Highly organic clays have a very weak and spongy feel at the plastic limit.

*Should read 425 µm.

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APPENDIX II

REPRESENTATIVE LIST OF ORGANIZATIONS IN LINER INDUSTRY

A. POLYMERIC MEMBRANE LINERS
   1. Polymer producers
   2. Manufacturers of polymeric membrane sheeting
   3. Fabricators of liners
   4. Installing contractors

B. BENTONITE PRODUCERS AND SUPPLIERS

C. OTHER LINER MATERIALS

D. MISCELLANEOUS ORGANIZATIONS IN THE LINER INDUSTRY

APPENDIX II

A. POLYMERIC MEMBRANE LINERS

1. Polymer Producers

DOW CHEMICAL COMPANY
2040 Dow Center
P.O. Box 1847
Midland, MI 48640

Contact: John L. Hartman
Product Sales Manager,
Chlorinated Polyethylene Designed Products Department
Phone: 517-636-1000

E.I. du PONT de NEMOURS AND CO., INC.
Elastomer Chemicals Dept.
Wilmington, DE 19898

Contact: Richard J. Arhart
Phone: 302-999-3160

Contact: Gerald E. Fisher
3245 Sunnyside Ave.
Brookfield, IL 66513
Phone: 312-485-6881

E.I. du PONT de NEMOURS AND CO., INC.
Explosive Products Division
1007 Market Street
Wilmington, DE 19898

Contact: Mr. T.J. Enright
Geotextile Product Manager
Phone: 302-774-1000

EXXON CHEMICAL CO.
Elastomer Technology Division
P.O. Box 45
Linden, NJ 07036

Contact:
Phone: 201-474-0100

HERCULES INCORPORATED
910 Market St.
Wilmington, DE 19899

Contact: Norman C. MacArthur
Product Manager, Elastomers
Phone: 302-575-6293

MONSANTO INDUSTRIAL CHEMICALS CO.
260 Springside Drive
Akron, OH 44313

Contact: Gary E. O'Connor
Project Manager
Commercial Development Department
Rubber Chemicals Division
Phone: 216-666-4111

PANTASOTE, INC.
26 Jefferson St.
Passaic, NJ 07055

Contact: Larry Kamp
Phone: 201-777-8500

POLYSAR, LTD.
Technical Development Division
Vidal Street
Sarnia, Ontario
Canada N7T 7M2

Contact: Carl Hancock
Phone: 519-337-8251

SHELL CHEMICAL COMPANY
605 N. Main Street
Altamont, IL 62411

Contact: Larry Watkins
Phone: 618-483-6517

UNIROYAL CHEMICAL COMPANY
Spencer Street
Naugatuck, CT 06488

Contact: Allen Crepeau
Phone: 203-723-3825

2. Manufacturers of Polymeric Membrane Sheetings

BURKE RUBBER COMPANY
2250 South Tenth St.
San Jose, CA 95112

Contact: D. Kutnewsky
Manager, Flexible Membranes
Phone: 408-297-3500

CARLISLE SYNTECH SYSTEMS
Division of Carlisle Corporation
P.O. Box 7000
Carlisle, PA 17013

Contact: William Witherow
Product Manager
Liners and Waterproofing
Phone: 717-245-7000

COLUMBUS COATED FABRICS
1280 N. Grant St.
Columbus, OH 43216

Contact: Lee Fishbein
Phone: 614-225-6069

COOLEY, INC.
50 Esten Ave.
Pawtucket, RI 02862

Contact: Paul Eagleston
Vice President
Phone: 401-724-9000

GACO
P.O. Box 88698
Seattle, WA 98188

Contact: Earle Johnson
San Jose, CA
Phone: 415-341-5661

B. F. GOODRICH COMPANY
Engineered Rubber Products Division
500 S. Main Street
Akron, OH 44318

Contact: R. D. Cunningham,
Sales Manager,
Environmental Products
Phone: 216-379-2226

GUNDLE LINING SYSTEMS, INC.
1340 East Richey Road
Houston, TX 77073

Contact: Richard K. Schmidt, President
Phone: 713-443-8564

HARTE & COMPANY
10 Link Drive
Rockleigh, NJ 076-1660

Contact: R. H. Dickinson
Phone: 201-767-1660

MAINLINE, INC.
3292 South Highway 97
Redmond, OR 97756

Contact: DeWitt Maine
Phone: 503-548-4207

OXFORD, INC.
220 Rainbow Blvd. North
Niagara Falls, NY 14303

Contact: Albert Hooper
Vice President
716-283-6900

PANTASOTE, INC.
26 Jefferson St.
Passaic, NJ 07055

Contact: Larry Kamp
201-777-8500

PLYMOUTH RUBBER COMPANY
104 Revere Street
Canton, MA 02021

Contact: Charles Neese
Phone: 617-828-0220

PROTECTIVE COATINGS, INC.
1602 Birchwood Ave.
Ft. Wayne, IN 46803

Contact: Elmo Murrell, President
Phone: 219-422-7503

SARNAFIL (U.S.), Inc.
Canton Commerce Center
Canton, MA 02021

Contact: Clark Gunness
Phone: 617-828-5400

SCHLEGEL LINING TECHNOLOGY, INC.
P.O. Box 7730
The Woodlands, TX 77380

Contact: James M. Price, President
Phone: 713-273-3066 (Conroe)
713-350-1813 (Houston)

SHELTER-RITE, INC.
Division of Seaman Corp.
P.O. Box 331
Millersburg, OH 44654

Contact: Dr. Bala Venktaraman,
Vice President,
Research and Development
Phone: 216-674-2015

STEVENS ELASTOMERIC & PLASTICS
PRODUCTS, INC.
27 Payson Ave.
Easthampton, MA 01073

Contact: Arnold G. Peterson
Phone: 413-527-0700

TENNECO CHEMICALS, INC.
P.O. Box 189
Piscataway, NJ 08805

Contact: Bob Hayes/Kent Turner
Phone: 201-356-2550

UNIROYAL, INC.
312 N. Hill St.
Mishawaka, IN 46544

Contact: D. L. Zimmerman
Phone: 212-256-8181

3. Fabricators of Liners

ADVANCE CONSTRUCTION SPECIALTIES
P. O. Box 17212
Memphis, TN 38117

Contact: H. M. VanNieuwenhuyze,
President
Phone: 901-362-0980

BROWN AND BROWN
P.O. Drawer 269
Mobile, AL 36601

Contact: Sam Brown, President
Phone: 205-479-6581

ELECTRA TARP, INC.
Park Centre
7241 Whipple Ave., N.W.
North Canton, OH 44720

Contact: Bob Fulmer, President
Phone: 216-497-1496

ENVIRONETICS, INC.
9824 Industrial Drive
Bridgeview, IL 60455

Contact: Ray Winters, President
Phone: 312-585-6000

FABRICO MANUFACTURING CORP.
1300 West Exchange Avenue
Chicago, IL 60609

Contact: Jay Sabath, Sales Manager
Phone: 312-254-4211

MCKITTRICK MUD CO.
P.O. Box 3343
Bakersfield, CA 93305

Contact: Bill Wheeler, President
Phone: 805-325-5013

PALCO LININGS, INC.
7571 Santa Rita Circle
P.O. Box 919
Stanton, CA 90680

Contact: Richard Cain,
President
Phone: 714-898-0867

POLY-PLASTICS
P.O. Box 299
Springfield, OH 45501

Contact: Roland Harmer, President
Phone: 513-323-4625

M. PUTTERMAN & CO.
2221 West 43rd Street
Chicago, IL 60609

Contact: A. Berman, President
312-927-4120

REVERE PLASTICS
16 Industrial Avenue
Little Ferry, NJ 07643

Contact: Larry Smith, President
Phone: 201-641-0777

SOUTHWEST CANVAS MFG. CO.
Oklahoma City, OK

Contact: Richard C. Nelson,
Manager
Phone: (405) 672-3355

STAFF INDUSTRIES
240 Chene Street
Detroit, MI 48207

Contact: Charles E. Staff,
President
Phone: (313) 259-1820
(800) 526-1368

SYNFLEX INDUSTRIES, INC.
2004-750 Jervis Street
Vancouver, British Columbia
Canada V6E 2A9

Contact: Gerald W. Salberg,
President
Phone: (604) 682-3621

WATERSAVER COMPANY, INC
5890 East 56th Avenue
Commerce City, CO

P. O. Box 16465
Denver, CO 80216

Contact: Bill Slifer,
Vice President
Phone: 303-623-4111

MANUFACTURERS WHO ALSO FABRICATE

Burke Rubber Company
Carlisle Tire and Rubber Co.
B. F. Goodrich
Schlegel Lining Technology, Inc.
Gundle Lining Systems

4. Installing Contractors

CRESTLINE SUPPLY CORP.
2987 South 300 West
Salt Lake City, UT 84115

Contact: Guy Woodward
Phone: 801-487-2233

ENVIROCLEAR, INC.
P.O. Box 242
Falls Village, CT 06031

Contact: Don Thompson, President
Phone: 212-997-0100
518-325-3332

GASTON CONTAINMENT SYSTEMS, INC.
1853 North Main Street
P.O. Box 1157
El Dorado, KS 67042

Contact: John Saenz
Phone: 316-321-5140

GLOBE LININGS, INC.
1901 East Wardlow Road
Long Beach, CA 90807

Contact: William Kays
Phone: 213-426-2587
213-636-6315

GULF SEAL CORPORATION
Suite 275
700 Regency Square Blvd.
Houston, TX 77036

Contact: William J. Way
Vice President &
General Manager
Phone: 713-782-9220

KEY ENTERPRISES, INC.
P. O. Box 6606
Odessa, TX 79760

Contact: Ken Stewart, President
Phone: 915-362-2368

MWM CONTRACTING CORP.
347 North Main Street
Milford, MI 48042

Contact: Joe McCullough
Phone: 313-685-9350
313-685-1201

NATIONAL SEAL CO, INC.
7701 East Kellogg
Wichita, KS 67202

Contact: John W. Owen
Phone: 316-681-1931

PACIFIC LININGS, INC.
P.O. Drawer GGGG
Indio, CA 92201

Contact: John Blatt, President
Phone: 714-347-0828

PLASTI-STEEL, INC.
3588 West 13th Street
Vickers-KSB&T Building
Wichita, KS 67203

Contact: M. C. Green, President
Phone: 316-262-6861

STA-FLEX CORPORATION
16 Post Road
Greenland, NH 03840

Contact: Lou Peloquin
4917 New Ramsey Ct.
San Jose, CA 95136
Phone: 408-224-0604

THE THURSTON WALLACE CO.
5470 East Evans Ave.
Denver, CO 80222

Contact: Cliff Heller, Vice President
Phone: 303-758-2232

TRI STATE CONSTRUCTION
959 108th Avenue, N.E.
Belleview, WA 98004

Contact: Joe Agostino
Phone: 206-455-2570

UNIT LINER CO
P. O. Box 789
Shawnee, OK 74884

Contact: J. A. Hendershot, President
Phone: 405-275-4600

FABRICATORS WHO ALSO INSTALL:

McKittrick Mud
Synflex Industries, Inc.

MANUFACTURERS WHO ALSO INSTALL:

B.F. Goodrich Company
Gundle Lining Systems, Inc.
Schlegel Lining Technology, Inc.

B. BENTONITE PRODUCERS AND SUPPLIERS

AMERICAN COLLOID COMPANY
5100 Suffield Court
Skokie, IL 60077

Contact: Nick Kesslering
Ryan F. McKendrick
Phone: 312-583-0400

ARCHER-DANIELS-MIDLAND
P.O. Box 15166
Commerce Station
Minneapolis, MN 55415

Contact:
Phone: 612-371-3400

ASHLAND CHEMICAL
9450 Midwest Avenue
Cleveland, OH 44125

Contact:
Phone: 216-587-2230

DOWELL
1150 North Utica Street
P. O. Box 21
Tulsa, OK 74102

Contact: Chris Parks
Mining and Construction
Technical Services
Phone: 918-560-2972

DRESSER MINERALS
P.O. Box 6504
Houston, TX 77005

Contact:
Phone: 713-972-2670

INTERNATIONAL MINERALS &
CHEMICAL CORP.
IMC FOUNDRY PRODUCTS
17350 Ryan Road
Detroit, MI 48212

Contact: G. Alther
Phone: 313-368-6000

CHARLES PFIZER & CO.
235 East 42nd Street
New York, NY 10017

Contact:
Phone: 212-573-2323

WILBUR ELLIS CO.
P.O. Box 1286
Fresno, CA 93715

Contact:
Phone: 209-226-1934

WYO-BEN PRODUCTS, INC.
P.O. Box 1979
Billings, MT 59103

Contact:
Phone: 406-252-6351

C. OTHER LINER MATERIALS

ARIZONA REFINING COMPANY
P.O. Box 1453
Phoenix, AZ 85001

Contact: J. R. Bagley, President
Phone: 602-258-4843

THE ASPHALT INSTITUTE
Asphalt Institute Building
College Park, MD 20740

Contact:
Phone: 301-277-2458

CHEVRON, USA, INC.
Asphalt Division
P. O. Box 7643
San Francisco, CA 94120

Contact: Kenneth Coleman
K. D. Coleman Co
P. O. Box 414
Santa Clara, CA 95052
Phone: 408-244-8948

I.U. MANAGEMENT SYSTEMS, INC.
1500 Walnut Street
Philadelphia, PA 19102

Contact:
Phone: 215-985-660

MICHELLE CORPORATION
Division of Weychem Canada Limited
P. O. Box 4794
Charleston Heights, SC 29405

Contact: F. Weyrich, President
Phone: 803-554-4033

PHILLIPS PETROLEUM COMPANY
Commercial Development Division
Bartlesville, OK 74004

Contact: Floyd H. Holland
Phone: 918-661-6428

PORTLAND CEMENT ASSOCIATION
Old Orchard Road
Skokie, IL 60076

Contact:
Phone 312-066-6200

D. MISCELLANEOUS ORGANIZATIONS IN LINER INDUSTRY

HOVATER-WAY ENGINEERS, INC.
23011 Moulton Parkway, Suite F-5
Laguna Hills, CA 92653

Contact: Louis R. Hovater
Phone: 714-830-4050

Type of service: Design engineering, specializing in membrane liners.

INQUIP ASSOCIATES, INC.
P.O. Box 2182
Santa Barbara, CA 93120

Contact: O.E. Hensgen
Phone: 805-963-6785

Type of service: Consulting, engineering, and contracting of various lining materials and slurry cut-off walls.

LINING MATERIALS
23011 Moulton Parkway, Suite F-4
Laguna Hills, CA 92653

Contact: George J. Miller,
General Manager
Phone: 714-581-9292

Type of service: Supplier of a variety of lining materials.

LIQUID CONTAINMENT SYSTEMS
P. O. Box 324
South Holland, IL 60473

Contact: Jack Moreland, President
Phone: 312-468-2500

Type of service: Design, planning, engineering, and installation of liners.

NATIONAL SANITATION FOUNDATION
NSF Building
Ann Arbor, MI 48105

Contact: Gary W. Sherlaw, Director
Standard Development
Phone: 313-769-8010

Type of service: Developing national specifications for membrane liners.

APPENDIX III-A

IMMERSION TEST OF MEMBRANE LINER MATERIALS FOR COMPATIBILITY WITH WASTES

(Matrecon Test Method 3 - August 1981)

Scope

This test is designed to assess, under accelerated conditions, the compatibility of polymeric membrane liner materials with specific wastes.

Summary of Method

Samples of the polymeric liner materials are fully immersed in a representative sample of the waste to be contained. Over a range of exposure periods, tests are run to determine the change in weight, dimensions, composition, and physical properties of the lining material as a function of time. One immersion sample is required for each immersion time or exposure condition.

Applicable Documents

- ASTM D297, "Rubber Products - Chemical Analysis".
- ASTM D412, "Rubber Properties in Tension".
- ASTM D624, "Rubber Property - Tear Resistance".
- ASTM D638, "Tensile Properties of Plastics".
- ASTM D1004, "Initial Tear Resistance of Plastic Film and Sheeting".
- ASTM D2240, "Rubber Property - Durometer Hardness".
- ASTM D3421, "Extraction and Analysis of Plasticizer Mixtures from Vinyl Chloride Plastics".
- FTMS 101B, Method 2065, "Puncture Resistance and Elongation Test (1/8 inch Radius Probe Method)".
- Matrecon Test Method 1, "Procedure for Determination of the Volatiles of Unexposed Membrane Liner Materials".
- Matrecon Test Method 2, "Procedure for Determination of the Extractable Content of Unexposed Membrane Lining Materials".

Equipment and Supplies:

Equipment:

- Exposure tank - minimum one gallon or four litre capacity, with provision for hanging specimens so that they do not touch bottom or sides of tank, or each other. Suggested arrangements are glass rods across top of tank, or stainless steel hooks fastened to tank lid.
- Stress-strain machine suitable for measuring tensile strength,tear resistance and puncture resistance.
- Jig for testing puncture resistance for use with FTMS 101B, Method 2065.
- Oven at 105±2°C.
- Dial micrometer.
- Analytical balance.
- Apparatus for running extractables, e.g. Soxhlet extractor or ASTM D297 rubber extraction apparatus.

Supplies:

- Labels and hangers for specimens, of materials known to be resistant to the specific waste. Hangers of stainless steel wire and tags made of 50 mil polypropylene, embossed with machinist's numbering dies and fastened with stainless steel wire, are resistant to most wastes.

Procedure

1. Obtain representative sample of the waste fluid. Note if fluid classifies or separates.
2. Perform the following tests on unexposed samples of the polymeric membrane liner materials:
    - 2.1. Percent volatiles, Matrecon Test Method 1 (Appendix III-D).
    - 2.2. Percent extractables with suitable solvent, Matrecon Test Method 2 (Appendix III-E).
    - 2.3. Tear resistance, machine and transverse directions, five specimens each direction. See Table III-A-1 for appropriate test method and recommended speed of test.
    - 2.4. Puncture resistance, five specimens, FTMS 101B, Method 2065.
    - 2.5. Tensile properties, machine and transverse directions, five

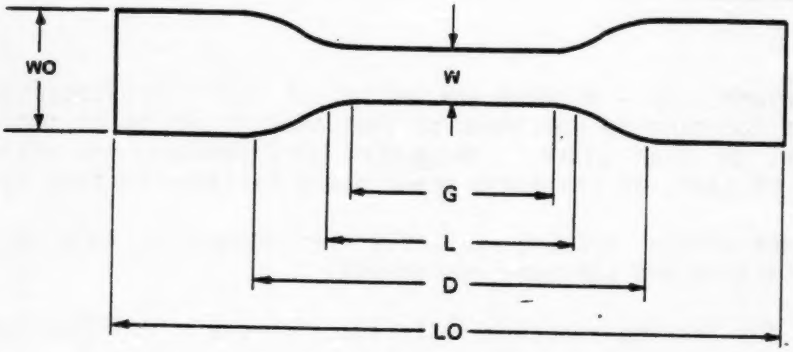

Figure III-A-1. Die for Goodyear dumbbell having the following dimensions:

W	Width of narrow section	0.25 inches
L	Length of narrow section	1.25 inches
WO	Width overall	0.625 inches
LO	Length overall	3.50 inches
G	Gage length	1.00 inches
D	Distance between grips	2.00 inches

Goodyear dumbbells (Figure III-A-1) each direction. See Table III-A-1 for appropriate test method, recommended test specimen, speed of test, and values to be reported.

2.6. Hardness, Duro A (Duro D if Duro A reading is greater than 80), ASTM D2240.

3. Cut a 6 x 8 inch piece of the lining material for each waste and each exposure period. Measure the following:
    3.1. Gage thickness, mil or mm - average of the four corners.
    3.2. Mass, g - to one-hundreth of a gram.
    3.3. Length, cm - average of the lengths of the two sides.
    3.4. Width, cm - average of the widths of the two ends.

4. Label the test specimen with a plastic identification tag and hang in sample of the waste fluid by a wire hanger.

    Note: In cases where the waste fluid is expected to stratify, the number of immersed specimens per exposure period can be increased so that test specimens exposed at each level of the waste can be tested.

5. At the end of the exposure, remove specimen from waste. Wipe off as much waste as possible and rinse well with water. Place wet specimen in a labelled polyethylene bag to prevent the specimen from drying out.

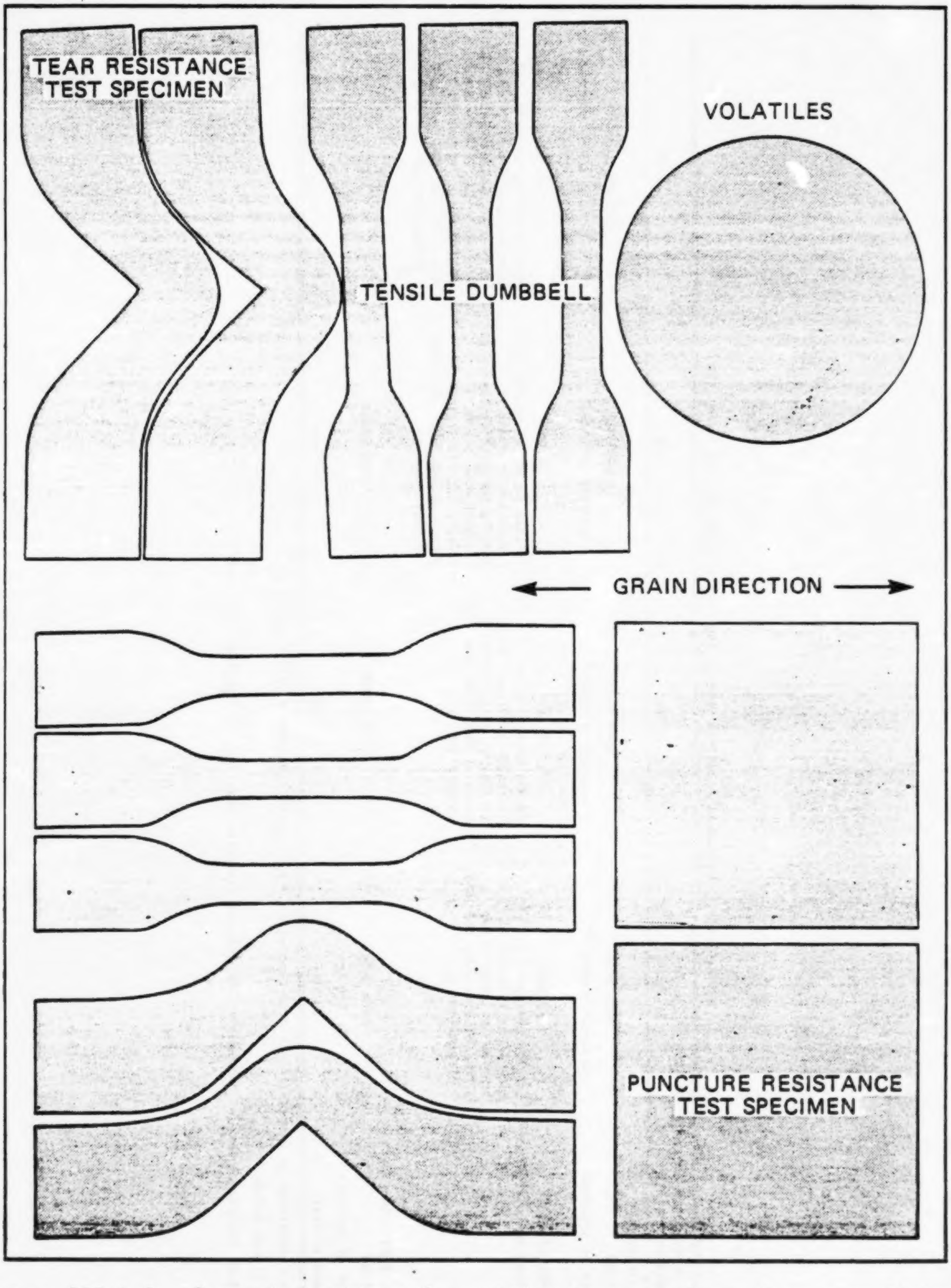
TEAR RESISTANCE TEST SPECIMEN
TENSILE DUMBBELL
VOLATILES
GRAIN DIRECTION
PUNCTURE RESISTANCE TEST SPECIMEN

Figure III-A-2. Suggested pattern for cutting test specimens from crosslinked, thermoplastic, or crystalline immersed liner samples.

TABLE III-A-1. RECOMMENDATIONS FOR TENSILE AND TEAR TESTING FOR IMMERSION STUDY

Type of compound and construction[a]	XL	TP	CX	FR
Tensile properties				
Method	ASTM D412	ASTM D638	ASTM D638	ASTM D751, Mtd B
Type of specimen	Goodyear dumbbell[b]	Goodyear dumbbell[b]	Goodyear dumbbell[b]	1" wide strip and 2" jaw separation
Speed of test	20 ipm	20 ipm	2 ipm	12 ipm
Values to be reported	Tensile strength, psi Elongation at break, % Tensile set after break, % Stress at 100, 200, and 300% elongation, psi	Tensile strength, psi Elongation at break, % Tensile set after break, % Stress at 100, 200, and 300% elongation, psi	Tensile stress at yield, psi Elongation at yield, % Tensile strength at break, psi Elongation at break, % Tensile set after break, % Stress at 100, 200, and 300% elongation, psi	Tensile at fabric break, ppi Elongation at fabric break, % Tensile at ultimate break, ppi Elongation at ultimate break, % Tensile set after break, % Stress at 100, 200, and 300% elongation, ppi
Tear resistance				
Method	ASTM D624	ASTM D1004	ASTM D1004	(c)
Type of specimen	Die C	...	...	...
Speed of test	20 ipm	20 ipm	2 ipm	...

[a] XL = Crosslinked or vulcanized; TP = thermoplastic; CX = crystalline; FR= fabric-reinforced.

[b] See Figure A-3-1.

[c] No tear resistance test is recommended for fabric-reinforced sheetings in the immersion study.

6. To test the immersed sample, remove wire hangers and identification label from specimen. Wipe off any remaining waste and rinse with deionized water. Blot specimen dry and measure the following:
    6.1. Thickness, mil or mm.
    6.2. Mass, g.
    6.3. Length, cm.
    6.4. Width, cm.

   The specimen should be returned to its polyethylene bag as soon as possible to prevent any loss of absorbed water.

7. Perform the following tests on the exposed specimen:
    7.1. Percent volatiles, Matrecon Test Method 7 (Appendix III-F).
    7.2. Percent extractables, Matrecon Test Method 7 (Appendix III-F).
    7.3. Tear resistance, machine and transverse directions, two specimens each direction. See Table III-A-1 for appropriate test method and recommended speed of test.
    7.4. Puncture resistance, two specimens, FTMS 101B, Method 2065.
    7.5. Tensile tests, machine and transverse directions, three specimens each direction. See Table III-A-1 for appropriate test method, the recommended test specimen and speed of test, and the values to be reported.
    7.6. Hardness, Duro A (Duro D if Duro A reading is greater than 80), ASTM D2240.

See Figure III-A-2 for a suggested cutting pattern.

8. Summarize the results as follows:
    8.1. Percent change in thickness.
    8.2. Percent change in mass.
    8.3. Percent change in area.
    8.4. Percent volatiles of unexposed and exposed liner material.
    8.5. Percent extractables of unexposed and exposed liner material.
    8.6. Percent retention of physical properties.
    8.7. Change, in points, of hardness reading.

9. Tests should be run over a range of exposure times. For compatiblity studies, the suggested range of exposure times is 0.5, 1, 2, and 4 months to five years.

10. Fresh waste fluid may be required to maintain concentration of constituents or to simulate actual service conditions.

APPENDIX III-B

TUB TEST OF POLYMERIC MEMBRANE LINERS

Scope:

The purpose of the tub test is to evaluate flexible membrane liner materials under conditions which simulate those that occur in actual service.

The effects of exposure to sun, temperature changes, ozone, and other weather factors can be evaluated, as well as the effect of a given waste on a specific liner. The fluctuation of the level of the waste is particularly significant in that an area of the liner is subjected to both the effects of the waste and weather. This alternating of conditions is especially harsh on liner materials and is usually encountered in the field.

Equipment and Supplies:

- Plywood to construct tubs and catch basin
- Pipe fittings and corks for tub and catch basin drains and plugs
- Meter stick or similar device to measure waste depth
- Thermometers
- pH meter
- Conductivity meter
- Drying oven
- Analytical balance
- Other equipment for chemical analyses, as needed.

Test specimen:

Piece of membrane liner, incorporating a field seam, large enough to fold over edges of the tub. Approximate size four feet by four feet.

Test Procedure:

The plywood tubs should be rectangular with sides sloping outward at a 1:2 slope. The dimensions of the tubs should be roughly 14" x 9" at the base, 25" x 20" at the top, and *ca*. 11" deep. Useful catch basin dimensions are 8 ft x 6 ft x 4 in (Figure III-B-1).

The liner specimen is draped over a tub and folded to fit the inside contours and edges of the tubs. The excess material is allowed to hang freely over the edges of the tub.

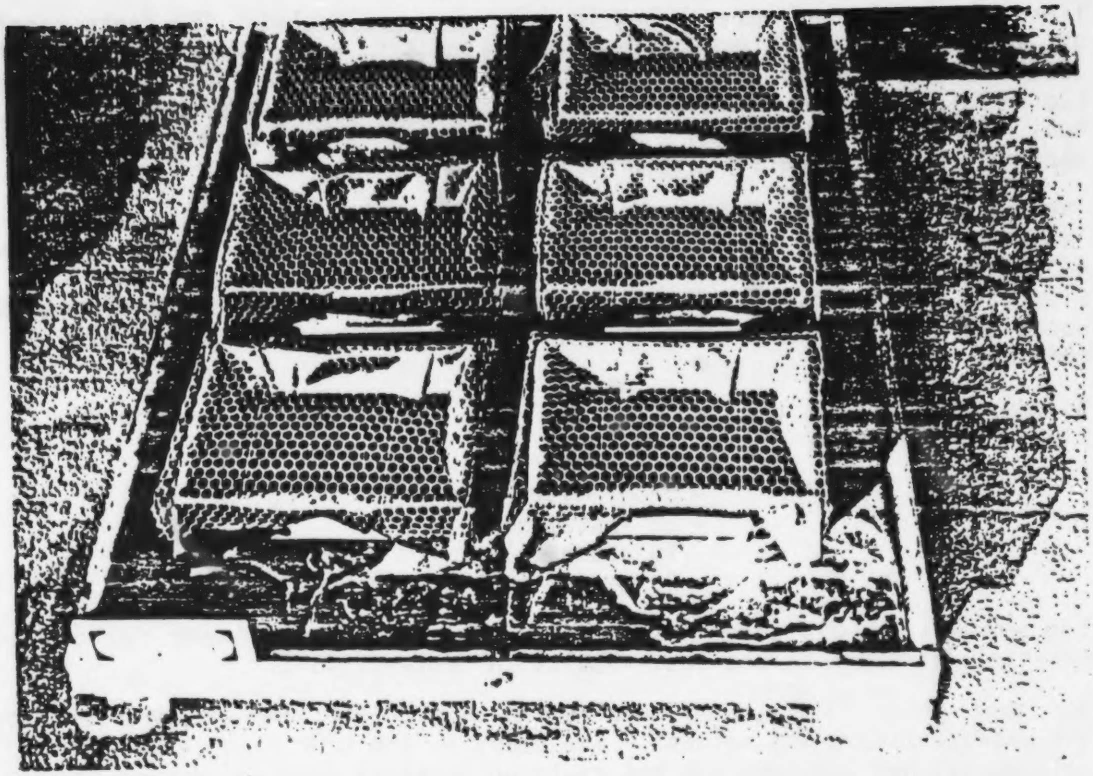

Figure III-B-1. The open exposure tubs lined with polymeric membranes and partially filled with hazardous wastes. They are covered with chicken wire and placed in a shallow basin lined with an elasticized polyolefin membrane. During rainy weather these cells are protected by a corrugated plastic cover (Haxo and White, 1977).

The tubs are filled from 3/4 to 7/8 full with wastes. The liquid level is allowed to fluctuate about 4 inches. During the exposure period the tub liners are inspected visually for cracking, opening of seams, and other forms of liner deterioration. The waste levels and temperatures are measured and recorded at regular intervals. Water is added when levels become too low. An oily waste which generally has a film of water at the surface tends to accumulate water (from dew) which does not evaporate significantly. Water, or actually an oil-water mixture, should be pumped from the bottom of these tubs to maintain liquid levels and prevent overflows of the waste. The oil-water mixture removed may be analyzed for pH, electrical conductivity, percent solids, and other parameters as appropriate. The water in the catch basin is also monitored for pH and conductivity as a possible indication of leakage from the tubs containing highly acidic or highly alkaline wastes.

Status of Tub Exposure Tests Underway in Oakland, California:

Long-term tub exposure tests on a roof in Oakland, California, were started in November, 1976 (Haxo et al, 1977). As of April 1980, only one of the 12 liner specimens that were placed in this test had failed. The tests consisted of 12 tubs utilizing four wastes (spent caustic, alkaline slop water, nitric acid waste, and a waste oil) and nine liner materials (elasticized polyolefin, two PVC's, polyester elastomer, butyl rubber, neoprene, EPDM, CSPE, and CPE). Most of the liners have swelled to some degree after an exposure period of approximately 3.5 years.

The elasticized polyolefin exposed to the waste oil developed cracks and leaked on the 517th day of exposure. This liner was observed to have swelled after one month of exposure and the swelling apparently continued at a very slow rate until failure. The elasticized polyolefin membrane developed in the waste/sun interface area, two openings which were oriented along folds in the membrane.

On removal from the tub, physical tests of the exposed liner were run at four exposure locations:

- Under waste only
- In waste/shade zone
- In shade only
- In waste/sunlight zone

The waste/sunlight zone provided the harshest environment for the liner material, as shown by the test results in Table III-B-1.

No other liner failure had occurred to April 1980, though deterioration of the exposed liners was evident. The seams in the EPDM liner exposed to nitric acid wastes had weakened and the caulking appeared cracked, but no leaking had been detected. The PVC liner below the acid waste has become hard. The liners tended to swell more at folds as well as in the waste/sun zone, indicating that both situations should be regularly examined on in-service liners. At the sharp corners, the butyl rubber liner was ozone cracking.

TABLE III-B-1. FAILED ELASTICIZED POLYOLEFIN LINER
EXPOSED TO SATURATED AND UNSATURATED OILS IN OPEN TUB[a]

Test	Original value	% Retention of property of exposure to Waste only	Waste + sun	Waste + shade	Shade only
Thickness, mils	23	113	113	113	98
Tensile strength, psi	2590	47	38	45	97
Elongation at break, %	665	89	81	83	99
Tensile set, %	445	76	72	74	100
S-100, psi	875	68	59	65	110
S-200, psi	970	64	46	63	107
Puncture resistance, lb.	26.3	97	73	70	135
Elongation, inches	0.97	130	122	113	142

[a] Exposure time: 506 days from 11/2/76 to 3/23/78.

APPENDIX III-C

TEST METHOD FOR THE PERMEABILITY OF COMPACTED CLAY SOILS
Constant Elevated Pressure Methods

INTRODUCTION

To assess the suitability of compacted clay soils for the lining of waste storage facilities, the primary laboratory measurement is saturated hydraulic conductivity or permeability. Such a measurement should be made on a specimen of soil that has been remolded and compacted in the range of optimum moisture content to achieve the maximum density possible for a given compactive effort. ASTM Methods D698-78 or D1557-78 should be used for determining a soil moisture-density relation.

Testing procedures recommended in subsequent paragraphs are not suitable for determination of field permeability values. They are, however, considered suitable for performing comparative studies to evaluate the potential influence of waste leachates on permeability of compacted clay soils that are candidates for use as liners. As a large variety of waste liquids are placed in hazardous waste landfills and surface impoundments (Chapter 2), there is a great need for a specific permeability test that can determine, in reasonable lengths of time, the potential effects these leachates may exert on permeability of clay liners.

In the selection of soils for lining a specific impoundment, the candidate soil or soils should be tested with the standard aqueous permeant and with a representative sample of the waste liquid to be impounded. The results will rank the soil-waste combinations and thus allow the choice of the most favorable soil for lining the facility.

The testing procedure is designed to reveal changes in permeability of the compacted soil specimen when the native soil solution (pore water) is replaced by the primary and/or secondary permeant. As a simulated native soil pore liquid, we recommend a 0.01 normal aqueous solution of calcium sulphate.

The permeameter used in this test (Figure III-C-1) is constructed from readily available and easily modified components. Standard compaction permeameters and the necessary ASTM procedures are available through most soil testing supply companies. All components in Figure III-C-1 are in common with the standard permeameter except for the enlarged liquid chamber, extended studs, high pressure fittings, Teflon outlet tubing, and Teflon gaskets. Figure III-C-2 is a schematic of a test setup utilizing permeameters.

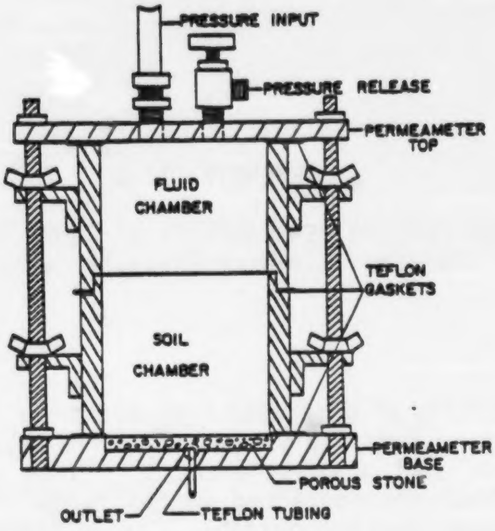
PRESSURE INPUT
PRESSURE RELEASE
PERMEAMETER TOP
FLUID CHAMBER
TEFLON GASKETS
SOIL CHAMBER
PERMEAMETER BASE
POROUS STONE
OUTLET
TEFLON TUBING

Figure III-C-1. Schematic of the compaction permeameter (Anderson et al, 1982).

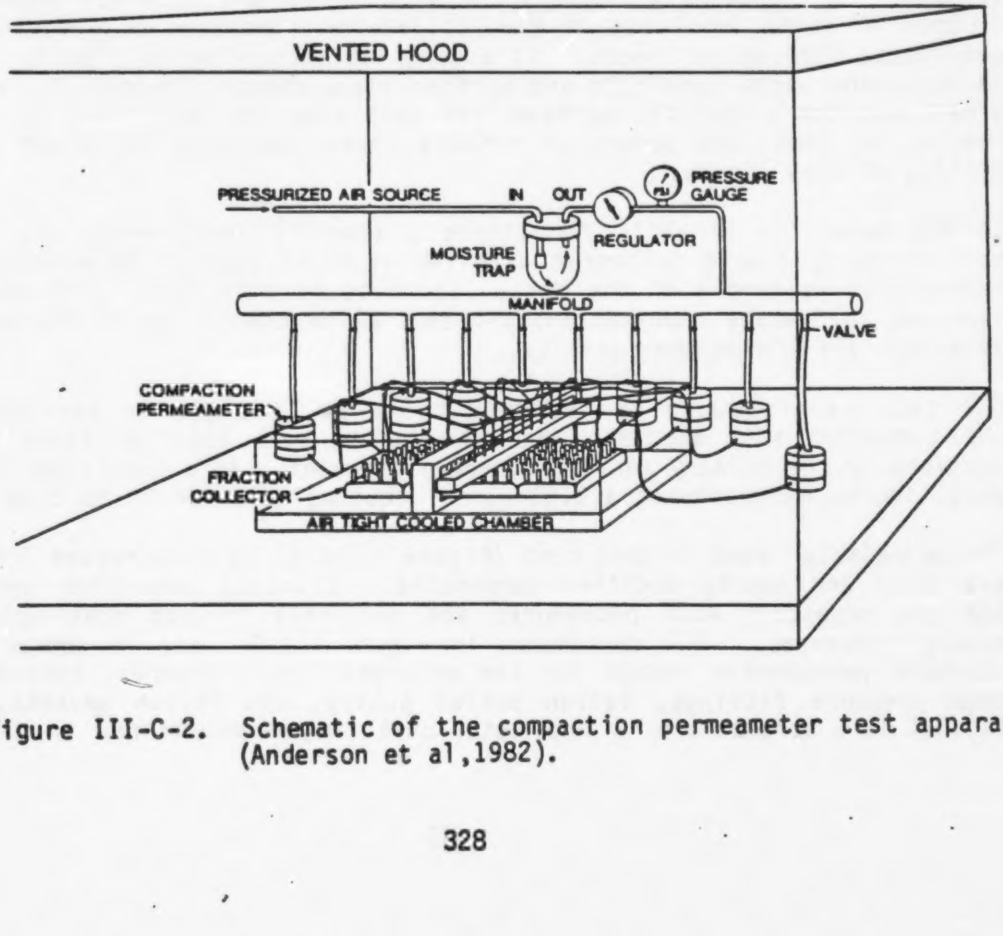
VENTED HOOD
PRESSURIZED AIR SOURCE
IN
OUT
PSI
PRESSURE GAUGE
REGULATOR
MOISTURE TRAP
MANIFOLD
VALVE
COMPACTION PERMEAMETER
FRACTION COLLECTOR
AIR TIGHT COOLED CHAMBER

Figure III-C-2. Schematic of the compaction permeameter test apparatus (Anderson et al,1982).

Compacted clay soils often have water permeability values lower than 10^{-8} cm sec^{-1} and it may be necessary to pass one pore volume of standard calcium sulphate permeant through a soil before a stable baseline permeability value is obtained. After establishing the permeability baseline, the passage of at least one pore volume of waste liquid may be necessary to determine fully the effects that the waste liquid may have on permeability of the compacted clay soil specimen. A pressurized air source should be used to increase the hydraulic gradient and thus reduce testing time (Bennett, 1966; Jones, 1960).

The use of large hydraulic gradients has shortcomings. The thickness of immobilized fluid films on soil particles may be substantially decreased at large pressures (Yong and Wartkentin, 1975). This would increase effective pore diameter available for liquid flow and thus increase permeability. Also, large hydraulic gradients can increase soil particle migration causing soil clogging and a resulting decrease in permeability (Olson and Daniel, 1979).

Criteria for selecting an appropriate hydraulic gradient depends greatly on proposed use of the permeability study. Where the objective is to estimate field permeability values, it has been suggested "to use gradients as close as those encountered in the field as is economically feasible" (Olson and Daniel, 1979). Zimmie (1981) suggested use of hydraulic gradients between 6 and 20 for laboratory studies attempting to duplicate field conditions.

In comparative permeability studies, larger hydraulic gradients are probably acceptable; however, care should be taken to monitor particle migration. Variations in permeant liquids may drastically change the permeability of a given soil (Michaels and Lin, 1954).

Comparative permeability studies use multiple permeameters to isolate effects of one or more variables. This testing approach has been widely used in agricultural irrigation studies evaluating the influence of various salt types and concentrations on soils of low permeability (McIntyre et al, 1979; McNeal, 1974). Comparative methods have also been used to evaluate the influence of organic liquids on soils (Michaels and Lin, 1954; Van Schaik, 1970).

In comparative permeability studies, flow should be laminar, and all but the variable being tested should be held constant. Under these conditions, any change in permeability can be interpreted as being the result of changes in the porous matrix. Soil permeability measurements must be carefully taken if they are to be accurate. Leaks, volatile losses, or channel flow along the interface of the permeameter and soil will greatly affect permeability values (Bowles, 1978).

Several authorities on permeability studies have expressed doubts that laboratory permeability tests are capable or reproducing field conditions. Olson and Daniel (1979) noted that the volume of soil samples used in laboratory tests is almost always too small to contain statistically significant distributions of macrofeatures encountered in the field (i.e. sand lenses, fissures, joints, channels, root holes, etc). They further noted that samples taken in the field may be affected either by the sampling method or selection of the most uniform or intact sample. Bowles (1978) stated that "the soil in the permeability device is never in the same state as in the field; it is always disturbed to some extent". Zimmie et al (1981) stated "it is virtually impossible to duplicate field hydraulic gradients in the laboratory. Test times become excessive and it becomes difficult to obtain accurate measurements of flows and heads at very low hydraulic gradients."

Several factors not incorporated into laboratory tests affect overall permeability of clay. Sherard and Decker (1977) listed primary factors determining "effective overall permeabiity" of a soil layer as being continuity, regularity, thickness, and characteristics of interbedded layers or lenses. Laboratory permeability determination on clay liners cannot account for this type of variability and can only attempt to characterize a homogeneous sample of clay soil. Other factors that may lead to discrepancies between field and laboratory permeability values are discussed in detail by Olson and Daniel (1979).

In the test procedure presented in this appendix, the following form of Darcy's Law may be used:

$$K = \frac{V}{AtH}$$

where:

K = Permeability (cm s^{-1})

V = Volume of liquid passed through the soil (cm^3)

A = Cross-sectional area of liquid flow (cm^2)

H = Hydraulic gradient = $\frac{h+l}{l}$

h = Hydraulic head (expressed as cm of water)

l = Thickness of soil specimen (cm).

t = Permeation time (second).

Permeability values are plotted along the Y-axis, while the cumulative number of pore volumes are plotted along the X-axis. The number of pore volumes is obtained by dividing the total volume of leachate (V) by the pore volume of the compacted soil specimen used in the test. (For an example plot, see Figures 4-1 to 4-9 in Chapter 4.)

If there is a failure in the clay liner being tested, a rough estimate of the time to failure of the real liner can be made by rearranging Darcy's law so that time is isolated as follows:

$$t = \frac{V}{AHK}$$

Assuming, for example, that a sharp permeability increase was recorded under $H = H_0$ at $t = t_0$ and estimating the highest possible gradient in the field equal to H_f (where $H_f \ll H_0$), the failure time of the soil liner, t_f, will be given by:

$$t_f = t_0 \frac{H_0}{H_f}$$

One should emphasize that this is not an analysis of the failure time, but only a rough estimate of it.

It is important to obtain a permeability value and time increment on each pore volume of leachate passed during a test. Failure to do so will make it impossible to plot permeability vs pore volume or to perform a "time failure" calculation for the clay soil liner.

EQUIPMENT

1. Soil crusher (C-2 Laboratory Crusher).
2. Soil grinder (Hewitt Soil Grinder).
3. 2 mm sieve (CB-810 Brass Sieves).
4. Moisture cans (LT-30 Tin Sample Boxes).
5. Balance capable of weighing 20 kg. (L-500 Heavy Duty Balance).
6. Drying oven (105°C) to determine water content of soil samples.
7. Compaction molds (CN-405 Standard Compaction Mold).
8. Compaction hammer (CN-4230 Mechanical Compactor).
9. Steel straight edge.
10. Permeameter bases and top plates (K-611 Permeameter Adapter).
11. A source of compressed air with a water trap, regulator and pressure meter.
12. A fraction collector with automatic timer for collection of samples over time (Brinkman Linear II Fraction Collector with a multiple distribution head).
13. An air tight, cooled chamber to limit volatile loss of samples during and after sampling.
14. A vented hood to hold the compaction permeameters and chamber containing the fraction collector. (This is a safety precaution to limit exposure of laboratory personnel to the hazardous chemicals used in the studies.)

Note: Equipment in Items 1, 3, 4, 5, 7, 8, and 10 can be obtained from Soil Test, Inc.; equipment in Item 2 can obtained from B. Hewitt Welding and Repair.

PROCEDURES

1. Obtain sufficient clay soil (ca 30 kg dry weight) to be tested. Approximately 3 kg dry weight of soil material is needed per compaction mold. Break the soil down to golf ball-sized clods and allow it to air dry.

2. Throughly break up the aggregation of the air dried soil and pass it through an ASTM No. 4 (4.75 mm) sieve. Where refined clay products are to be admixed with a native-soil, thoroughly mix the materials at this point. To improve the reproductibility of a mixture, proper proportions should be determined using percentage by oven dry weight. Do not oven dry the actual materials to be blended as this could alter chemical and physical properties of the liner material.

3. After thoroughly mixing, the soil should be placed in air tight containers and stored at room temperature until the time of test.

4. Determine the moisture density relations of the soil on five to seven specimens using ASTM Method D698-78 or D1557-78.

5. Use the remaining soil to prepare compaction molds at optimum moisture content. Weigh all compaction molds before and after placement of the soil material to permit the determination of the bulk density, porosity, and pore volume of each specimen.

6. Fit a valve on top of the permeameter top plate with pressure fittings and connect it to a source of air pressure via copper tubing. Place a water trap, pressure regulator, and pressure gage in line between the air pressure source and permeameter. The water trap should be placed between the pressure source and regulator to prevent buildup of debris on the membrane in the regulator. The pressure gage should be loaded between the regulator and a pressure manifold to the permeameters so that the hydraulic head being exerted on the clay soils can be monitored. Permeameters used for testing of clay liners must be capable of safely operating with hazardous materials including industrial solvents, volatile compounds, corrosive acids, and strong bases. All gaskets used in permeameters should be Teflon to prevent deterioration and possible blowout from contact with these aggressive permeant liquids. To avoid leakage around the hard Teflon gaskets, all metal surfaces against which the gaskets seat should be wiped clean of grit. Permeameter components have been found to withstand continous operational use at pressures up to 60 psi.

   Volatile losses may occur during sample delivery from the outlet tubing to the leachate collection bottles. To limit these volatile losses, the top of each leachate collection bottle should be fitted with a long stem funnel and placed in an air-tight cooled compartment. When volatile hazardous chemicals are used, the entire test apparatus should be set in a vented hood.

7. Place the standard permeant (0.01N $CaSO_4$) in the chamber above the compacted soil. To avoid channel formation, clay should be allowed to seat at low pressure. By allowing standard permeant to stand on the soil for 24 hours, an effective seat is obtained for the top few millimeters of the clay core. This thin layer will minimize the possibility of bulk flow along the permeameter sidewalls. The rest of the specimen should adequately seal when the permeant is forced into the compacted soil specimen at elevated pressures. With several specimens producing leachate, it may be desirable to have an automatic fraction collector. This is especially useful with long-term tests.

8. To limit the volume for diffusive mixing of leachate samples after they have passed through a compacted specimen, the leachate outlet should be fitted with an adapter to 3 mm (inside diameter) Teflon tubing. The use of translucent Teflon at the permeameter outlet provides a convenient window through which to monitor the expulsion of entrapped air. Standard permeant should be passed through the permeameter until no air bubbles are visible in the outlet tubing. If soil piping occurs, eluted soil clays will be visible either clinging to the inside walls of the outlet tubing or as a suspension in the collected samples. The liquid chamber should be completely filled, and a constant pressure applied through the pressure input (10 psi should be sufficient to reduce testing time and minimize particle migration in the soil). This constant pressure should be maintained until no air bubbles are visible in the outlet tubing and a constant permeability value is obtained. If the constant (equilibrium) permeability values are not consistently below 1×10^{-7} cm sec^{-1}, the soil is probably not suitable as a liner material.

9. Depressurize the permeameter and remove the top plate and liquid chamber. If the soil has shrunk, it is probably not suitable as a liner material.

10. If the soil has expanded into the liquid chamber, remove the excess soil with a straight edge without smearing the soil surface, collect all the removed soil material and obtain its oven dry weight to permit recalculating bulk density, porosity, and pore volume of the soil specimen. If the soil surface is smeared during the removal of the excess soil, pass standard leachate to assure that the permeability has not been altered.

11. Place the waste permeant in the liquid chambers of the permeameters and repressurize the system. Maintain at least two permeameters with standard permeant for the duration of the tests. Where both a primary and secondary leachate are expected to be generated by the waste, each waste liquid should be used on at least two permeameters. To collect the primary leachate, fill a large Buchner funnel with the waste and subject it to sufficient suction to extract the liquids present in the waste. Repeat this procedure until approximately

two liters of primary leachate (per permeameter) has been generated. Secondary leachate should be generated by the standard EPA procedure agreed upon at the time of test. For example, shake 5 kg of waste with 2.5 liters of water (per permeameter). The resulting solution can be filtered using a large Buchner funnel.

12. Pass at least one pore volume of the appropriate permeant through the soil specimen. If the specimen exhibits a trend of increasing permeability, pass an additional pore volume of the leachate through the soil. If the soil specimen maintains a permeability below 1×10^{-7} cm sec^{-1} and exhibits a decreasing or stable permeability after passage of the first pore volume, the permeameter should be disassembled to examine the soil specimen.

13. If the soil specimen has shrunk, it is unlikely to be suitable as a liner material.

14. If the soil specimen has expanded, repeat the above procedures beginning with Step 10.

15. If the soil specimen has not changed volume, reassemble the permeameter and place the standard permeant (0.01N $CaSO_4$) in the liquid chamber. Pass additional standard permeant. If the permeability of the soil has consistently stayed below 1×10^{-7} cm sec^{-1} as measured with the standard, primary, and secondary leachate, proceed to Step 16.

16. Examine the translucent Teflon outlet tubing for signs of particle migration out of the soil specimen. If there is evidence of soil migration, pass an additional standard permeant to observe if the internal erosion continues. If it continues, the soil probably will not be suitable for use as a liner material. If the soil migration stops, proceed to Step 17.

17. Depressurize the system and extrude the soil specimen from the compaction mold to examine it for signs of cracking, internal erosion or soil piping, dissolution, structural changes, or any other difference from the soil specimens that received only standard leachate. If there are none of the above signs that the soil has deterioriated due to contact with the waste leachate, the soil should be suitable as a liner material to contain that particular waste.

Comments

This procedure is designed to reveal changes in flow properties due to the replacement of the soil solution (the standard aqueous permeant) by a waste liquid. The procedure is quite involved and requires considerable effort to perform. However, considering the significance of the problem, which is the storage of hazardous wastes in a continuously safe impoundment, the task of carefully identifying and understanding the impact of wastes on soil flow properties must be undertaken.

At present, a designer cannot rely on available data and a body of past experience because such data do not exist. The difficulties that are linked with determining the permeability of a compacted soil liner specimen for a particular waste are primarily connected with the following two testing conditions:

1. Compacted soil specimens will have low permeabilities, e.g. less than 10^{-7} cm sec^{-1}. Under such circumstances, a considerable time is required to obtain a steady K value, even when the standard permeant liquid is used.

2. To assess the effect of water replacement by a waste, almost a complete replacement has to take place. This requires the passage of at least two pore volumes of waste liquid through the specimen. For a specimen with a permeability equal to 10^{-8} cm sec^{-1}, even a hydraulic gradient as large as 300 may require several months if the specimen is of a reasonable size, for example D = L = 3 inches. To decrease specimen thickness will certainly be a waste of effort since the test condition may not then simulate the field situation.

It is acknowledged that the recommended test procedure is a research project but, at the present time, no shortcuts are available; however, this procedure must be undertaken in order to generate raw data to be used in the design of the waste soil liner.

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APPENDIX III-C. TEST METHOD FOR THE PERMEABILITY OF COMPACTED CLAY SOILS

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APPENDIX III-D

VOLATILES TEST OF UNEXPOSED POLYMERIC LINING MATERIALS
(Matrecon Test Method 1 - October 1982)

Scope

This test is to be performed on unexposed membrane liner materials.

Significance

This test can be used to determine the volatile content of an unexposed sheeting, including water, volatile oils, and solvents. Nonvolatile dissolved or absorbed components of a specimen will be determined by the extractables test which is run after the volatiles have been removed (see Matrecon Test Method 2). The volatile content should be determined as soon as possible after the liner has been received. By identifying the orientation of the disk with respect to the sheeting at the time it was died out, the grain of the sheeting can be established.

Definitions

Volatiles are the fraction of weight lost by a specimen during the specified heating process described below.

Apparatus

- Two-inch interior diameter circular die.
- Analytical balance.
- Air oven.

Test Specimen:

Two-inch diameter disks died out of the sheeting, as received.

Number of Test Specimens:

All determinations should be run in duplicate.

Procedure:

1. Draw a line on the sheeting to mark "grain" or machine direction. If the "grain" is unknown, draw a random straight line on the sheeting.

2. Die out a two-inch diameter disk so that the lines fall approximately in the middle of the specimen.

3. Weigh specimen in tared, closed container to the nearest 0.0001 g. Record weight "as received weight".

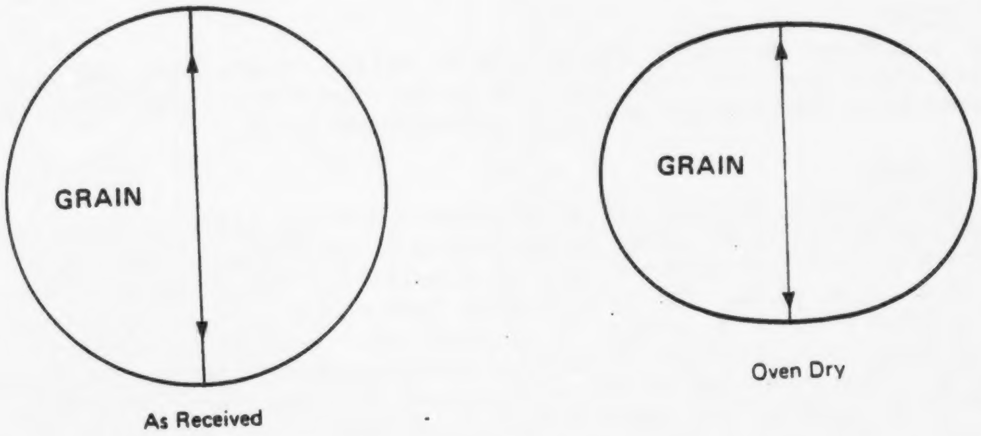
4. Dry specimen out on Teflon screen for two hours at 105±2°C.

5. Cool in desiccator for 20 minutes.

6. Weigh on analytical balance to 0.0001 g; record as the "oven dry weight".

7. Measure diameters in machine and transverse directions. Record to 0.001 inches.

8. If machine direction is unknown, find and record largest and smallest diameters of disk. Mark small diameter as machine direction on disk as shown in Figure III-D-1. Use the dried disk to determine the orientation of the sheeting from which it was removed.



As Received

Oven Dry

Figure III-D-1. Machine direction determination.

9. Retain specimens for additional testing, e.g. specific gravity, thermogravimetry, extractables, etc.

Calculations

Calculate the percent volatiles as follows:

Volatiles, % = [(A-B)/A] x 100

where:
A = grams of specimen, "as received weight"
B = grams of specimen, "oven dry weight"

Report

1. Identification of sheeting.

2. Result of above calculation of volatiles.

APPENDIX III-E

TEST FOR THE EXTRACTABLE CONTENT OF UNEXPOSED LINING MATERIALS
(Matrecon Test Method 2 - October 1982)

Scope

This procedure covers the extraction of plasticizers, oils, and other solvent-soluble constituents of polymeric lining materials with a solvent that neither decomposes nor dissolves the polymer.

References

This procedure generally follows ASTM D3421, "Extraction and Analysis of Plasticizers Mixtures from Vinyl Chloride Plastics". See also ASTM D297, "Rubber Products-Chemical Analysis", paragraphs 16-18.

Significance

The extractable content of a polymeric lining material can consist of plasticizers, oils, or other solvent-soluble constituents that impart or help maintain specific properties such as flexibility and processability. During exposure to a waste, the extractables content may be extracted out by the waste resulting in a change in properties. Another possibility is that during exposure the material could absorb non-volatilizable constituents from a waste. Measuring the extractable content of unexposed lining materials is, therefore, useful for monitoring the effect of an exposure on a lining material. The extract and the extracted liner obtained by this procedure can be used for further analytical testing. e.g. gas chromatography, infrared, ash, thermogravimetry, etc. for fingerprinting the liner.

Apparatus

- Aluminum weighing dishes.
- Analytical balance.
- Air oven.
- Soxhlet extractor (or rubber extraction apparatus).
- Extraction thimbles.
- 500 mL flat-bottomed flask (or 400 mL thin-walled Erlenmeyer flask if rubber extraction apparatus is used).
- Hot plate or steam plate.
- Boiling beads.
- Cotton wool.
- Aluminum foil.

Note: Because HCl splits out during the extraction of PVC and CPE, the rubber extraction apparatus may be substituted for the Soxhlet with all polymers except PVC and CPE. An appropriate reduction in sample size and solvent volume must be made.

Reagents

Table III-E-1 lists the recommended solvents for the extraction of membrane liners of each polymer type.

TABLE III-E-1. SOLVENTS FOR EXTRACTION OF POLYMERIC MEMBRANES

Polymer type	Extraction solvent
Butyl rubber (IIR)	Methyl ethyl ketone
Chlorinated polyethylene (CPE)	n-Heptane
Chlorosulfonated polyethylene (CSPE)	Acetone
Elasticized polyolefin	Methyl ethyl ketone
Epichlorhydrin rubber (CO and ECO)	Methyl ethyl ketone or acetone
Ethylene propylene rubber (EPDM)	Methyl ethyl ketone
Neoprene	Acetone
Nitrile rubber (vulcanized)	Acetone
Nitrile-modified polyvinyl chloride	2:1 blend of carbon tetrachloride and methyl alcohol
Polyester elastomer	Methyl ethyl ketone
High-density polyethylene (HDPE)	Methyl ethyl ketone
Polyvinyl chloride (PVC)	2:1 blend of carbon tetrachloride and methyl alcohol
Thermoplastic olefinic elastomer	Methyl ethyl ketone

Note: Because lining materials can be sheetings based on polymeric alloys which are marketed under a trade name or under the name of only one of polymers, this list can only be taken as a guideline for choosing a suitable solvent for determining the extractables. Once a suitable solvent has been found, it is important that the same solvent be used for determining the extractables across the range of exposure periods.

Sample size

If using the Soxhlet extractor, about five grams of devolatilized material are needed per extraction. If using the rubber extraction apparatus, about two grams are needed. All extractions should be run in duplicate.

Procedure

1. Cut the sample into cubes no larger than 0.25" on a side.
2. Weigh sample into an aluminum weighing dish and dry in moving air at room temperature for more than 16 hours.
3. Place in air oven for two hours at 105±2°C. Weigh the sample.
4. Weigh the sample into a tared extraction thimble. Plug small thimbles with a piece of cotton wool to prevent the pieces from floating out of the thimble. (Large thimbles are tall enough to stay above the level of the liquid.)

5a. For PVC and CPE materials: Add 200 mL of extraction solvent to the 500 mL flat-bottom distillation flask. Add boiling beads to reduce bumping.

5b. For other materials: Dry and preweigh a thin-walled Erlenmeyer distillation flask. Add 200 mL of extraction solvent to the flask.

6. Place the thimble in the extractor barrel, put the condensor in place, and run the extraction a minimum of 22 hours. Aluminum foil can be wrapped around the extractor and flask to increase the distillation rate.

7a. For PVC and CPE materials: When the extraction is complete, rinse all the solvent from the extractor barrel into the distillation flask. Decant the solvent from the flask into a dried, tared 500 mL Erlenmeyer flask and then evaporate on a steam bath with filtered air. Place the flask in an oven at 70±2°C and dry two hours. Hold the extract for further testing e.g. gas chromatography and infrared.

7b. For other materials: When the extraction is complete, rinse all the solvent from the extractor barrel into the distillation flask. Evaporate the solvent from the flask on a steam bath with filtered air. Place the flask in an oven at 70±2°C and dry two hours. Hold the extract for further testing.

8. If the extract contains constituents which may volatilize during the evaporation procedure or is to be used for further analysis, heat the flask with extract in solution on a 70°C hot plate or a steam plate to near dryness. Complete evaporation of solvent in vacuum oven at 40°C.

9. Remove extracted liner from the thimble after excess solvent is removed and place in a tared aluminum weighing dish. Heat to constant weight at 105°C. Extracted PVC specimens cannot be dried to a constant weight at 105°C when they are extracted with a blend of CCl_4 and CH_3OH. It is recommended that the sample be dried 72 hours at 105°C, Hold the extracted liner for further testing.

Note: In cases where the extracted specimen sticks to the extraction thimble, the extraction thimble should be dried to constant weight at 70°C before the extraction and the weight recorded as the true weight of the thimble. After the extraction, the extracted liner can be dried to a constant weight in the thimble.

Calculations

Calculate the percent volatiles as follows:

$$\text{Volatiles, \%} = [(A-B)/A] \times 100$$

where:

A = grams of specimen, as received
B = grams of specimen after 2 hours at 105°C

Calculate the percent extractables as follows:

Extractables, % = (B/A) x 100

where:
A = grams of specimen
B = grams of dried extract

Note: In cases where the extract may contain some constituents which volatilized while the extraction solvent was evaporated, the percent extractables should also be calculated as follows:

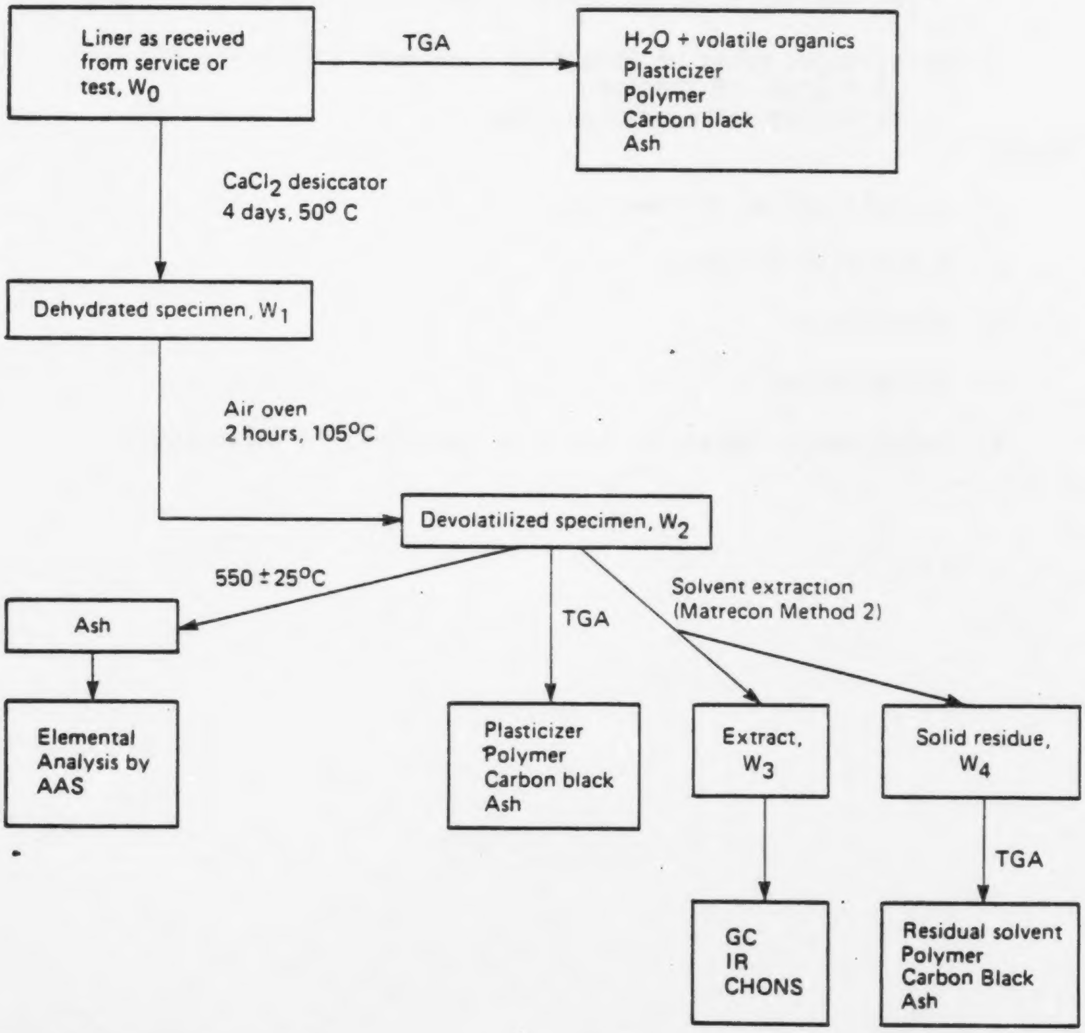
Extractables based on loss from specimen, % = [(A-B)/A]
A = grams of specimen
B = grams of extracted liner

Report

1. Identification of sheeting.
2. Extraction solvent.
3. Volatiles.
4. Extractables.
5. Extractables based on loss from specimen, if calculated.

APPENDIX III-F

ANALYSIS OF EXPOSED POLYMERIC LINING MATERIALS
(Matrecon Test Method 7)


Liner as received from service or test, W_0
TGA
H_2O + volatile organics
Plasticizer
Polymer
Carbon black
Ash
$CaCl_2$ desiccator
4 days, 50° C
Dehydrated specimen, W_1
Air oven
2 hours, 105°C
Devolatilized specimen, W_2
550 ± 25°C
Ash
Elemental Analysis by AAS
TGA
Plasticizer
Polymer
Carbon black
Ash
Solvent extraction
(Matrecon Method 2)
Extract, W_3
Solid residue, W_4
GC
IR
CHONS
TGA
Residual solvent
Polymer
Carbon Black
Ash

TGA = thermogravimetric analysis
GC = gas chromatography
IR = infrared spectroscopy
AAS = atomic absorption spectroscopy
CHONS = carbon, hydrogen, nitrogen, oxygen, and sulfur determination

APPENDIX IV
INSTALLATION OF FLEXIBLE POLYMERIC MEMBRANE LINERS

The installation of flexible membrane liners requires a significant planning effort prior to construction. This planning effort must include consideration of the storage and security of all necessary equipment, installation equipment, manpower requirements, the placement operation, field seaming, anchoring and sealing, quality control, inspection, and protection of placed liners. These considerations are discussed in detail in this Appendix.

IV.1 On-site Storage of Materials and Equipment.

Items requiring storage will include the liner materials and all equipment necessary for installation. Figure IV-1 shows liner material packaged and shipped to the site. Most liner material is packaged in folded panels or rolls which may weigh from 2,000 to 5,000 pounds each. All membrane liners should be stored out of sunlight if possible to prevent their degradation and to minimize blocking. Blocking occurs when the liner material sticks together, causing delamination or ripping when the roll is unrolled onto the subgrade. Figure IV-2 shows the result of blocking of a reinforced liner, with the scrim exposed. This damage will have to be repaired. Liners are shipped rolled or accordion folded in cardboard boxes and placed on wooden pallets. The liner material can thus be moved from the storage site to the construction site by means of a fork-lift truck, or some other suitable piece of equipment, without damage.

An important consideration in the storage of all equipment and liner materials at the site is prevention of vandalism and theft. This can be accomplished by erecting a temporary fence or placing the material in an existing secured area. The need for an elaborate storage system can be minimized if the job can be planned so that all equipment and materials necessary can be brought to the site, and installation begun immediately after receipt of liner materials and location of equipment at the site.

IV.2 Installation Equipment

Necessary equipment needed to install flexible membrane liners depends on the type of liner material to be installed, the complexity of the job with respect to side slope steepness, the number of penetrations, the number of seals required, and the length of installation time anticipated. Some means to move the liner material from storage to the impoundment site is necessary. A fork-lift truck is very useful for this purpose, though other pieces of equipment, such as a backhoe or front-end loader, can also be used. High-density polyethylene liner material is brought to the site in rolls rather than pallets and requires a crane or front-end loader for moving to the installation site.

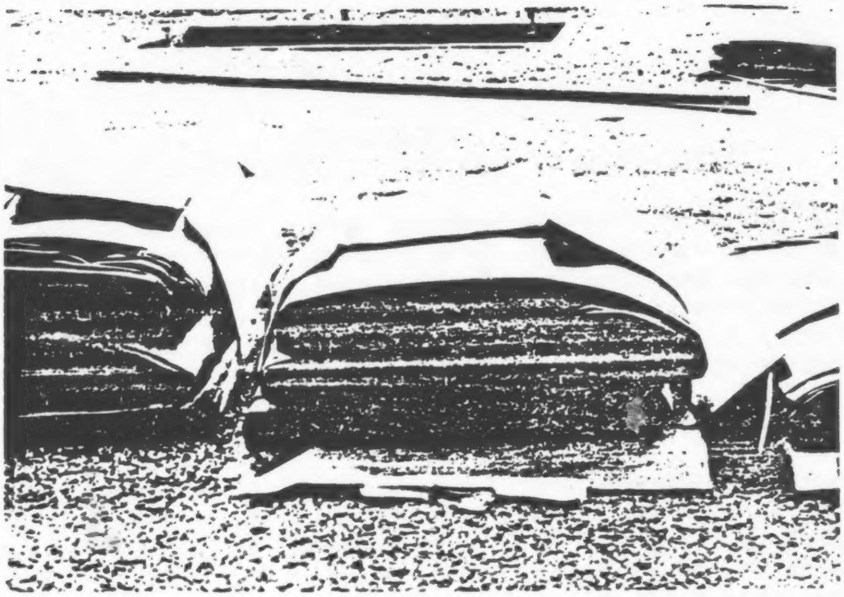


Figure IV-1. Liner panels are shipped to the site on wooden pallets either rolled or accordion folded.

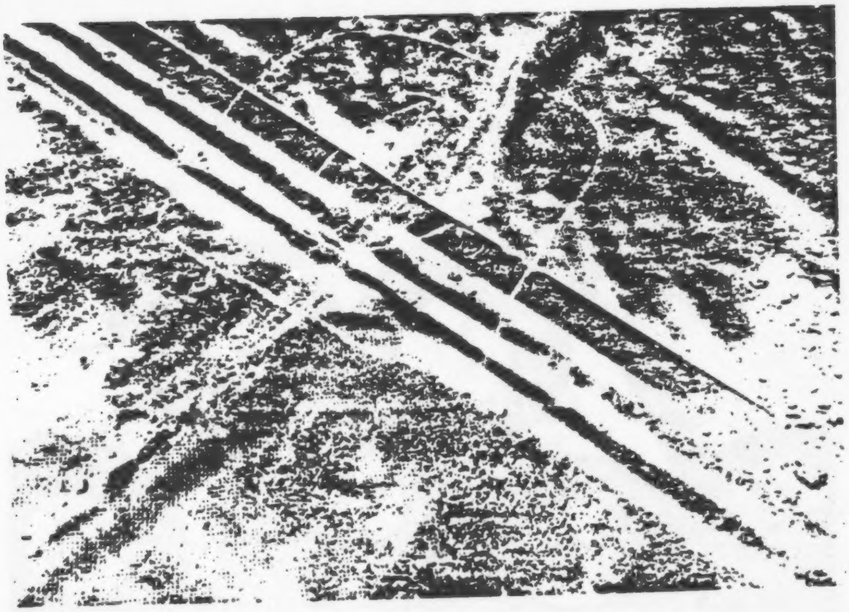


Figure IV-2. Damage to a fabric reinforced liner caused by "blocking" of the sheeting. Blocking can occur during shipping or storage when sheeting is rolled or folded and sticks together under warm conditions. The exposed fabric scrim must be repaired.

These rolls may weigh up to 10,000 pounds and special straps are used to move them (Figure IV-3).

A backhoe may prove useful if touch up work on subgrade preparation is required during installation. A backhoe or front-end loader can also be used to move sand to the top of the slopes so that sand bags can be filled to prevent the wind from damaging panels that are placed prior to seaming.

The majority of liner materials are solvent seamed in the field. Hand rollers are used to obtain a good surface bond. High-density polyethylene is heat-welded and requires specialized equipment. This includes an automatic welder which can be raised or lowered along the side slope of the impoundment. A hand welder is also used. Figure IV-4 shows the hand welder and the automatic welder being lowered down the side slope by a winch.

For liner materials which require the use of rollers in the field seaming, a board at least one inch thick, 12 inches wide, and up to 12 feet long should be available for each seaming crew to use. This board provides support during seaming and is placed under the overlap of the liner material. As seaming progresses, the board is slid along underneath the seam to provide a good seaming surface. These boards normally have ropes tied to the front so that they can be pulled along underneath the seam as the seaming crew moves from the middle of the panel to the ends. Figure IV-5 shows the rope attached to a seaming board which is properly located beneath the seam.

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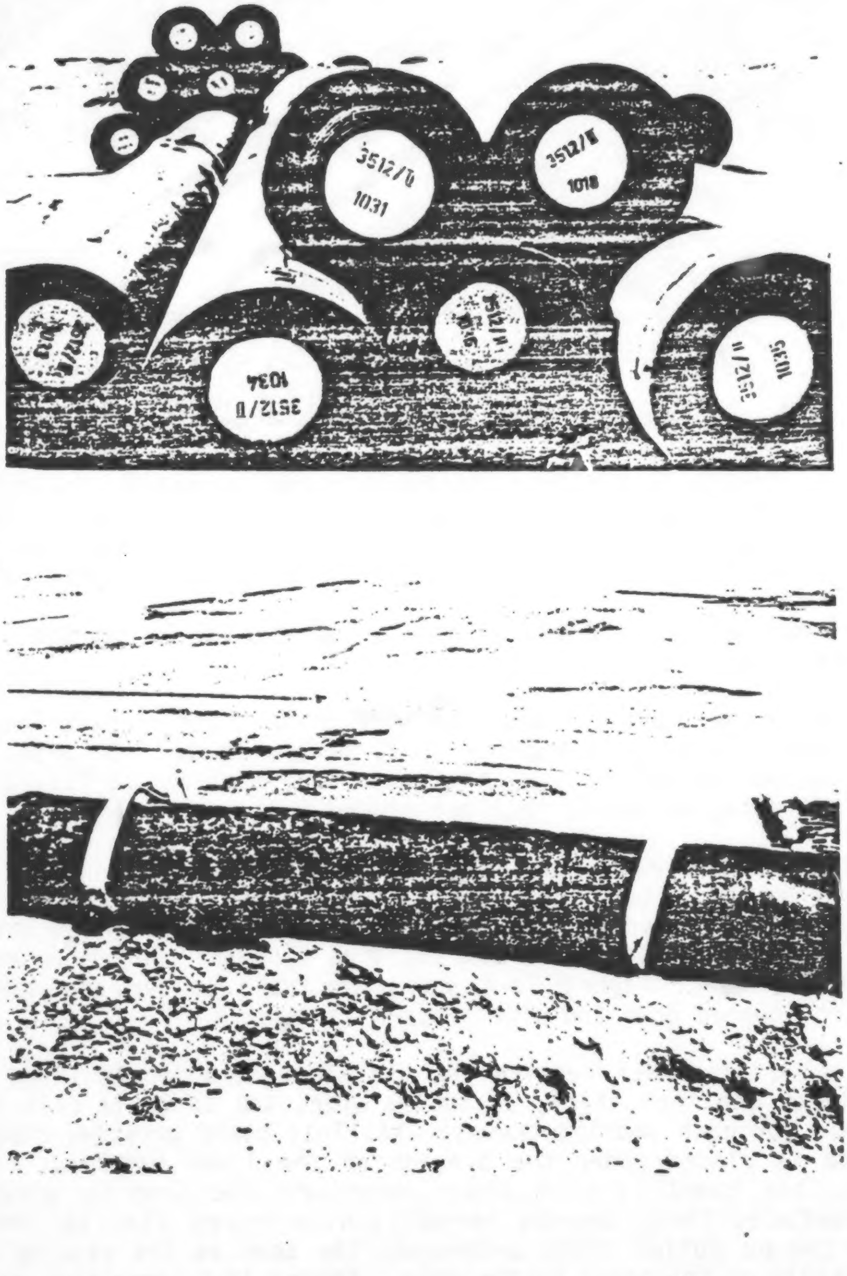
3512/II
1031
3512/II
1018
3512/II
1034

Figure IV-3. High-density polyethylene (HDPE) is shipped to the site rolled onto drums. Each roll may weigh up to five tons.

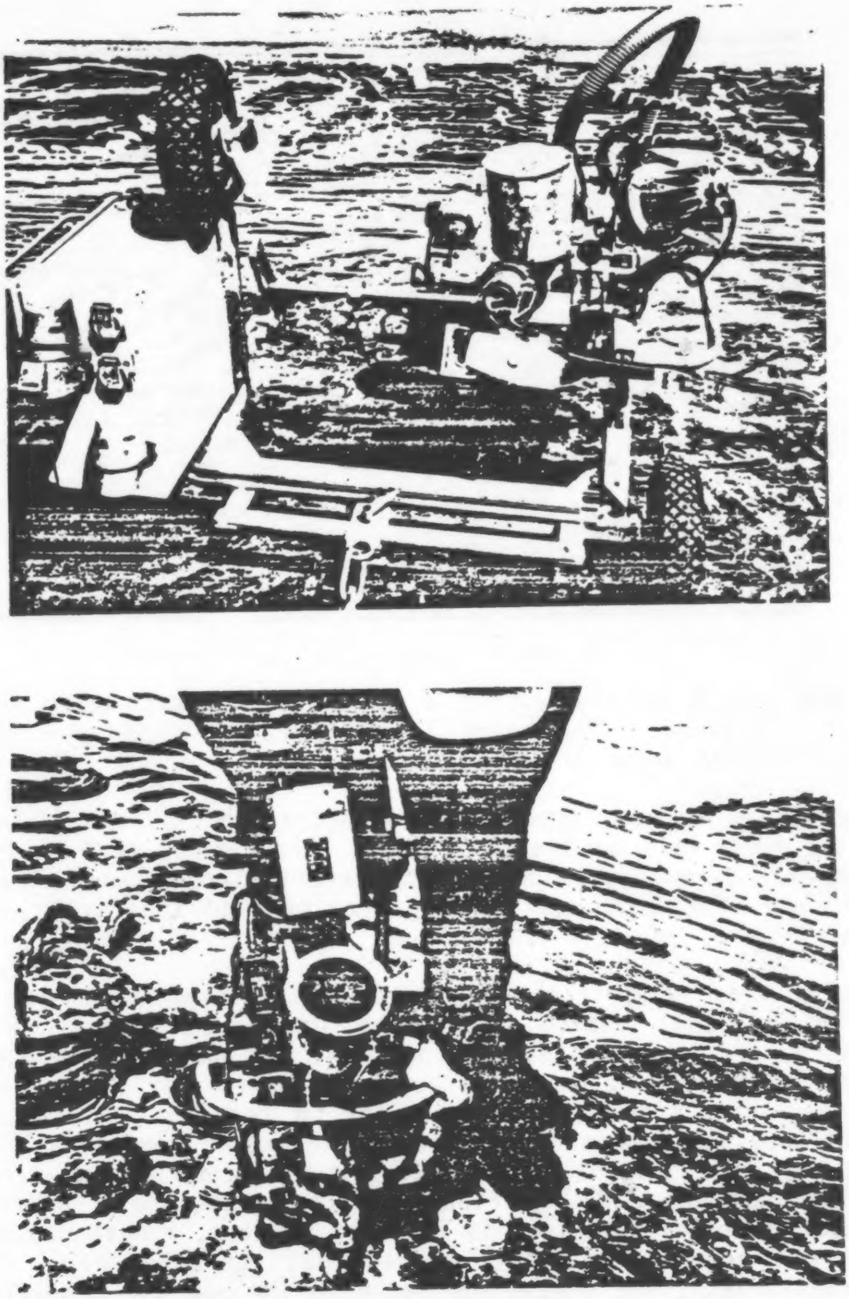

Figure IV-4. Special equipment for seaming of high-density polyethylene (HDPE). An automatic welder is shown above; a hand held welder is shown below. With both devices molten HDPE is extruded between the overlap of the two sheets being seamed.

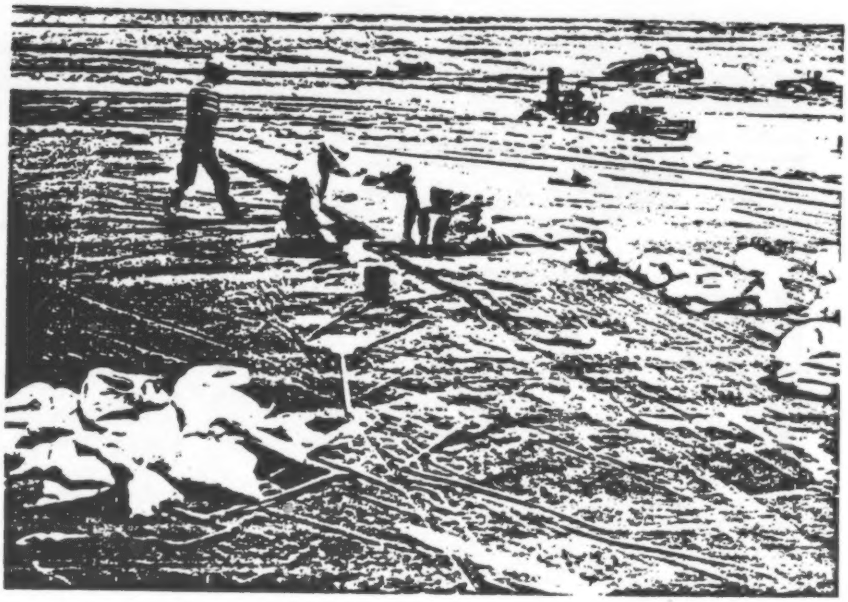

Figure IV-5. This crew is using a board for support under the area being seamed. The board is pulled along under the liner with the rope shown in the picture.

It is necessary to have some means to control the effects of wind on panels which have been laid on the subgrade. This can be accomplished using old tires, or more commonly, sandbags placed every five to ten feet along unseamed edges. Figure IV-6 shows how sandbags can be used to prevent wind damage to liner material.

Many of the liner materials require surface cleaning where the seam is to be made prior to actual seaming. Therefore, a sufficient supply of clean cotton rags must be available to the seaming crew. In addition, natural brushes and stainless steel scouring pads are necessary, particularly for seaming CSPE, as the surface cure must be removed prior to seaming. Heat guns should be available when solvent seaming is to take place. These guns provide a means to bring the liner material to a suitable temperature in the event the ambient temperatures are below 60° F. Figure IV-7 shows the use of a heat gun to warm the liner. If trichlorethylene is used for seaming, a heat gun should be used with extreme caution, as toxic phosgene gas can be formed. Seaming crews using trichloroethylene should not smoke on the job as inhalation of smoking materials in the presence of trichloroethylene produces the same phosgene gas. Respirators are often needed, especially when crew members must work in confined areas and use solvents. An electric generator and sufficient extension cords are necessary if heat guns are used. A crayon should be available for marking the location of seams prior to the application of solvents. Additional equipment needed for the installation of liners includes caulking compounds and caulking guns, pails for washing solvents, paint brushes or

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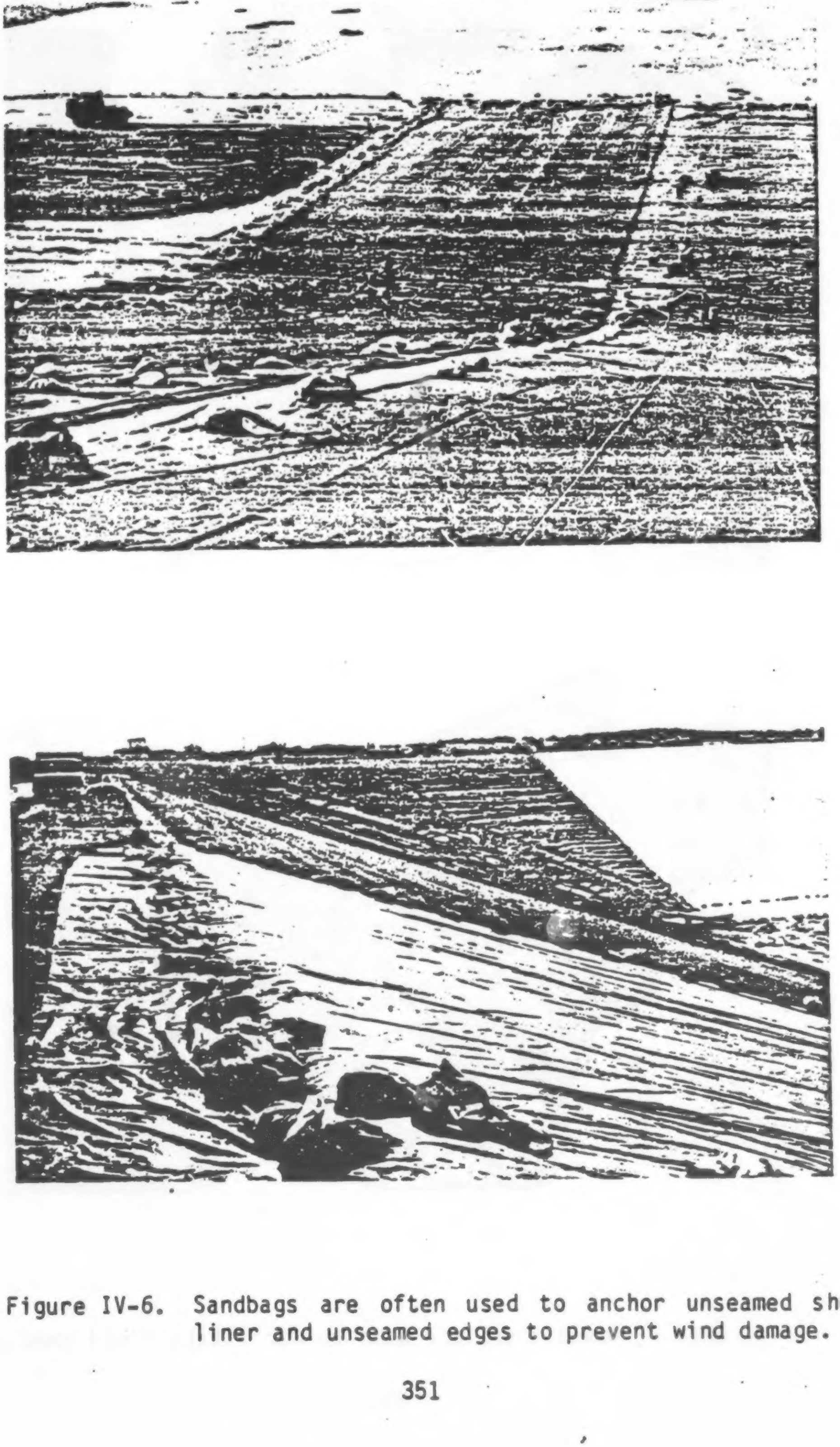

Figure IV-6. Sandbags are often used to anchor unseamed sheets of liner and unseamed edges to prevent wind damage.

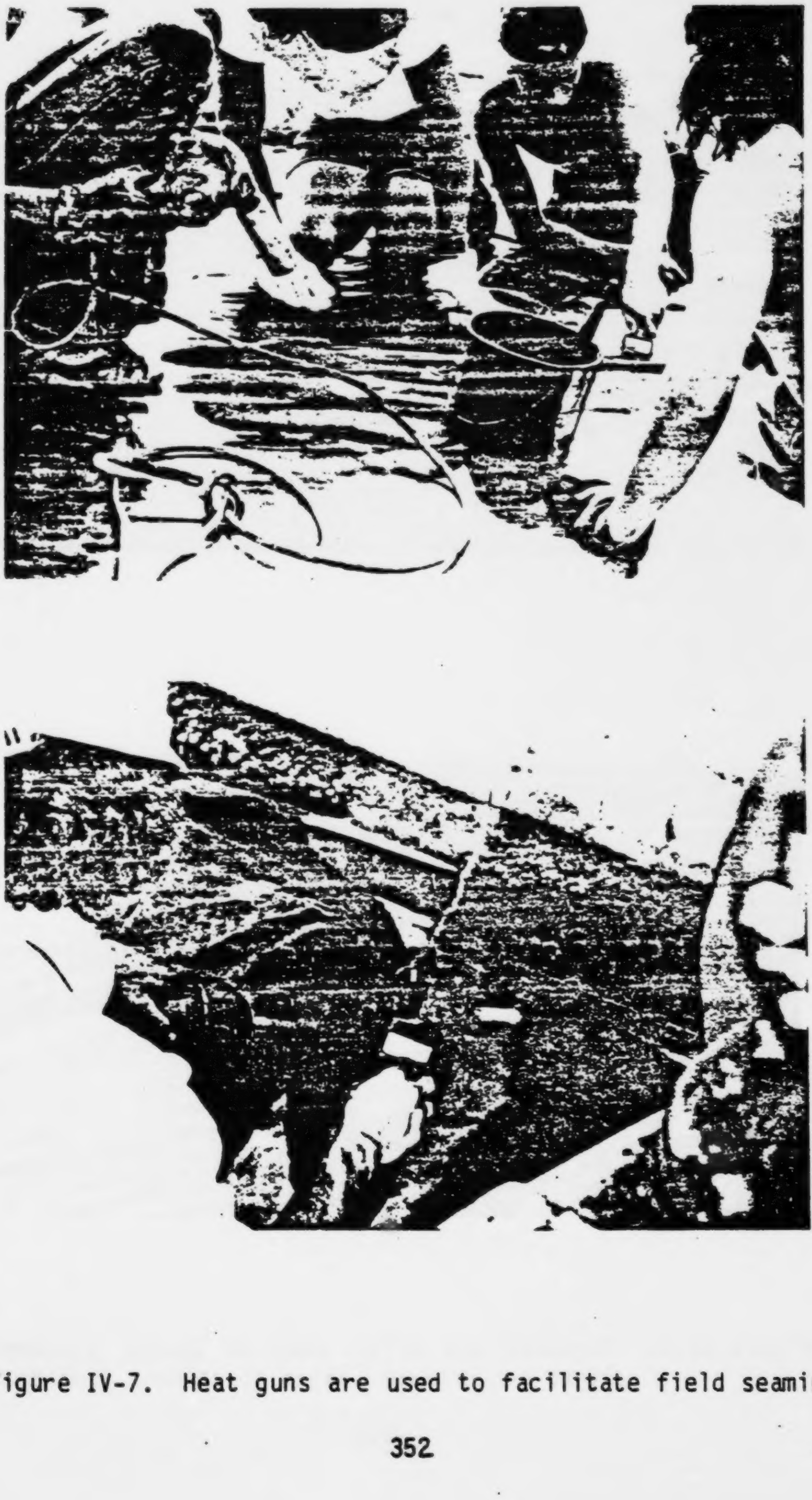

Figure IV-7. Heat guns are used to facilitate field seaming.

other applicators, solvent resistant gloves, safety goggles for men working with solvents, knee pads, shoes with flat soles to prevent damage to the liner, scissors and a utility knife, hand-held earth tampers, hand rakes and shovels, stakes and string to help in the spotting of the panels.

Large sections or panels of a liner are often moved across the subgrade by field crews. Wooden dowel rods should be provided to the field crew to use in moving panels without stretching the edges which will be seamed. These dowel rods are placed on the edge of the panel; the panel is then rolled onto the dowel rod. This provides a handle so that the panels can be moved without stretching the liner.

A list of the equipment often required for installation of membrane liners is presented in Table IV-1.

IV.3 Manpower Requirements

Manpower requirement for the installation of liner materials is obviously a function of the rate that the installer wants to place panels and accomplish field seaming. Typically, installation contractors will have anywhere from five to ten people on site when placing one panel at a time. Generally, a crew foreman will direct the activities of the field crew. He may not directly participate in the unrolling and spotting of panels or in field seaming. However, he must be experienced in installation of the specific liner material.

Crew size requirements also depend on the complexity of the installation and the experience of the field crew. If the majority of the crew members are recruited locally, they probably will require training during installation. At the present time, the trend is toward having installation contractors retain field supervisors who travel from job site to job site. Large jobs where crews perform specific tasks may involve many people. This occurs where one crew unrolls panels, another crew spots the panels, and a third crew performs all field seaming. Crew sizes also depend on the number of structures or penetrations in the facility. For example, if three or four concrete pillars are located within the area of one panel, this situation will require more manpower than if the panel is to be placed on a flat subgrade. In many instances, the owner of the facility may provide necessary manpower on an as-needed basis to the installation contractor. This arrangement will minimize the direct cost of installation to the owner, as excess work loads can be fulfilled with temporary labor.

IV.4 Liner Placement

Table IV-2 enumerates principal considerations that installers should follow in placing a specific liner. Before moving panels from the storage site to the installation location a number of tasks must be performed. The anchor trench around the perimeter of the installation should be completed. The dirt excavated from the anchor trench should be raked smooth so that the panels can be unrolled along and parallel to the anchor trench in the width direction. Other things that must be accomplished prior to panel spotting are: (1) the

TABLE IV-1. EQUIPMENT AND MATERIALS FOR INSTALLATION OF FLEXIBLE MEMBRANE LINERS

Item	Use
Fork lift	To move liner panels and backfill anchor trenches.
Tires, sandbags	To anchor unseamed panels to prevent wind damage.
Proper adhesives	To make field seams and seal liner around concrete or steel penetrations.
Portable electric generator	To operate heat guns or lighting for working at night.
Air lance	Quality control testing of field seams.
Vacuum box	Testing the integrity of field seams.
Hand-held earth tampers	To smooth subgrade as necessary.
Miscellaneous materials:	For field seaming.
- Adhesive applicators (paint brushes, caulking guns, rollers, etc.).	
- Liner preparation equipment: clean rags, scrub brushes, scouring pads, pails for solvent, hard surface rollers, seaming support board, heat guns, crayons for marking, dowels for pulling panels, stakes and chalk line, steel measuring tape, scissors and utility knives, electrical extension cords (for heat guns).	
Field crew equipment:	For field crew when making seams.
- Safety goggles, solvent resistant gloves, knee pads, respirators, soft soled shoes.	
First aid kit	In case of accidents.
Air compressor	Supply air that might be needed when working with solvents, and for air lance.

TABLE IV-2. CONSIDERATIONS DURING LINER PLACEMENT

Follow manufacturers' recommended procedures for adhesive system, seam overlap, and sealing to concrete.

Use a qualified installation contractor having experience with membrane liner installation, preferably the generic type of liner being installed.

Plan and implement a quality control program which will help insure that the liner meets specification and the job is installed per specifications. Inspection should be documented for review and record keeping.

Installation should be done during dry, moderately warm weather if possible.

Subgrade should be firm, flat, and free of sharp rocks or debris.

subgrade should be raked smooth or compacted if necessary; (2) there should be no standing water in the impoundment; (3) any concrete structures that must be seamed around should be prepared prior to unrolling of any panels; (4) if skirts are to be used around footings on concrete structures, these must be in place prior to the beginning of panel placement; (5) any outflow or inflow structures or other appurtenances should be in place.

Placement often begins with the unfolding or rolling of the panels lengthwise as shown in Figure IV-8. The panels are then unfolded in the width direction, either down the side slope or across the floor (Figure IV-9). The field crew then begins to position or "spot" the panel into its proper location, (Figure IV-10). As panels are spotted and seamed togetner, sand bags are placed as shown in Figure IV-6 The instructions on the boxes containing the liner must be followed to assure the panels are unrolled in the proper direction with the correct side exposed for seaming (Figure IV-11). The panels should be pulled relatively smooth over the subgrade (Figure IV-12). If the subgrade is smooth and compacted, then the liner should be relatively flat on the subgrade. However, sufficient slack must be left in the material to accommodate any possible shrinkage due to temperature changes.

IV-5 Field Seaming

The panels should be unfolded and spotted so that a sufficient seam overlap of the adjacent panel is maintained. Figure IV-13 shows two examples of proper overlap. Seam overlap varies with liner manufacturer and the liner type. Recommended overlaps vary from 4 to 12 inches. Figure IV-14 illustrates typical factory and field seams.

Field seaming is a critical factor in flexible membrane liner placement. The liner manufacturers have recommended procedures and adhesive systems for achieving successful field seams. If the manufacturer does not have a recommended bonding system, then the use of that liner material should be questioned. Generally three methods are used to seam materials in the field. These

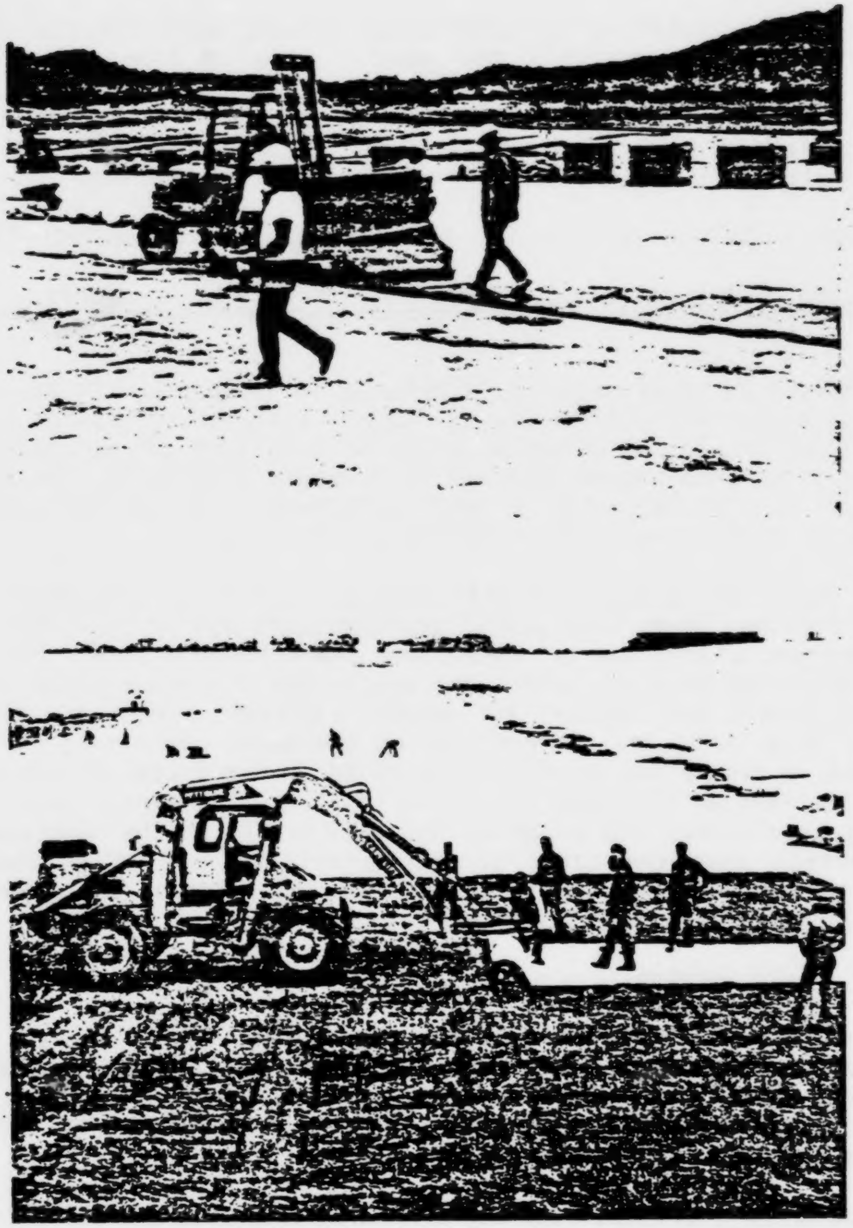

Figure IV-8. The panels of liner membrane are unfolded or unrolled.

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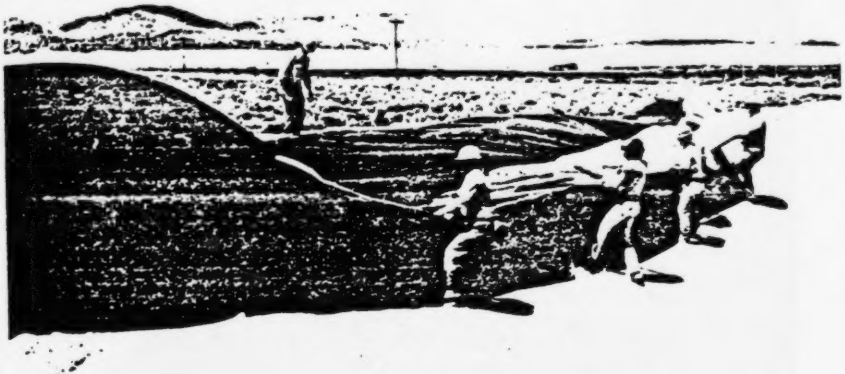

Figure IV-9. Workmen "pull" the panel across the subgrade. This step may be difficult to accomplish during windy conditions.

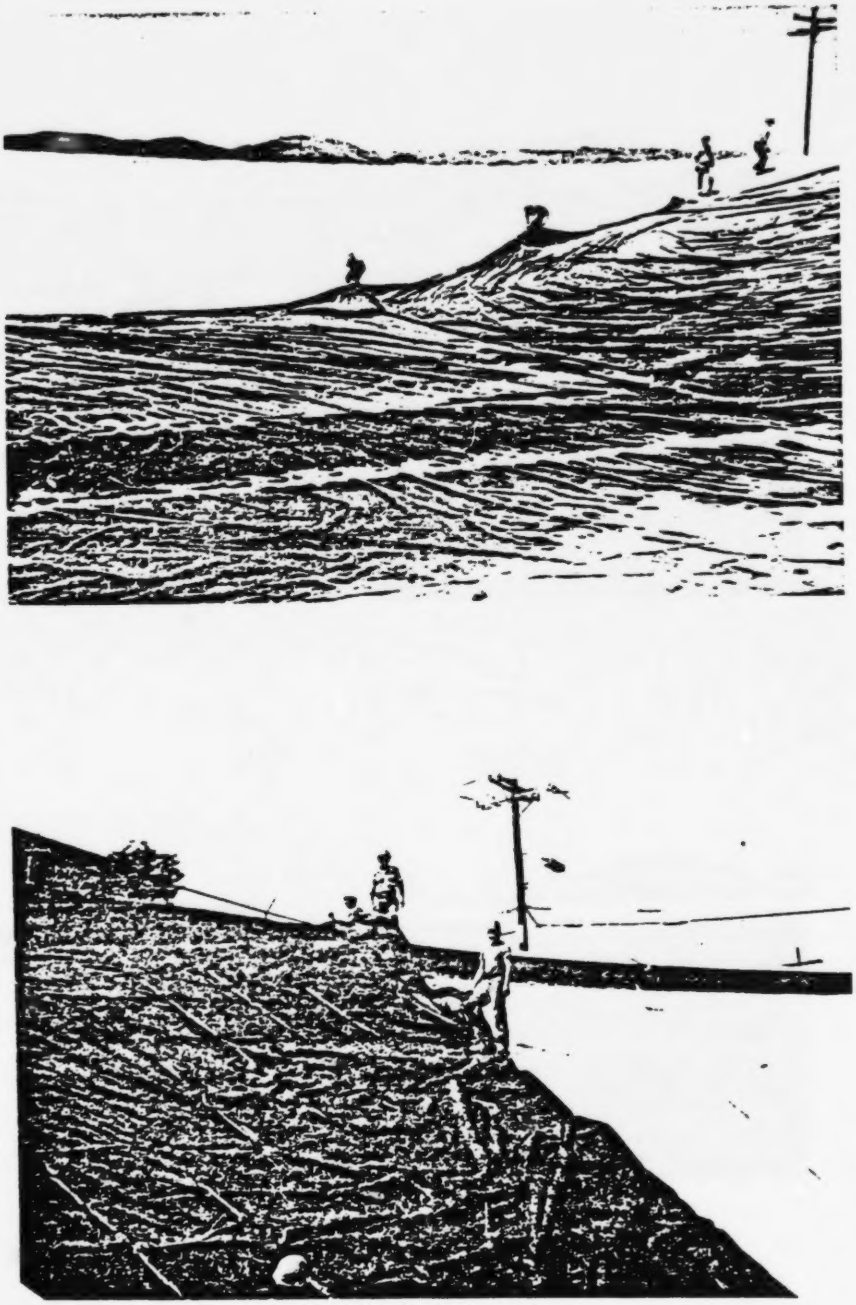

Figure IV-10. Once a panel has been unfolded, the crew "spots" or positions it in the proper location.

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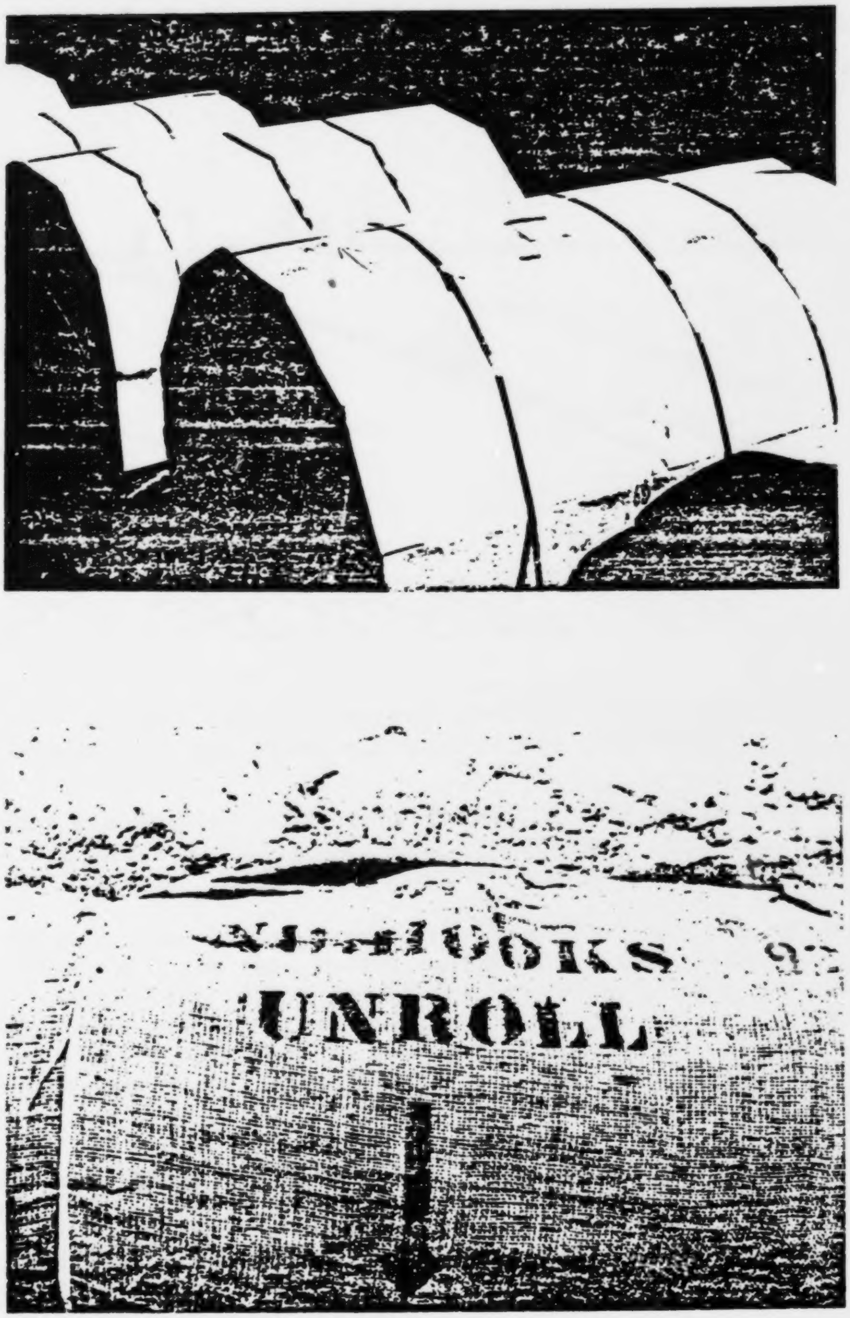

Figure IV-11. The instructions for unrolling liner panels are clearly shown on each container.

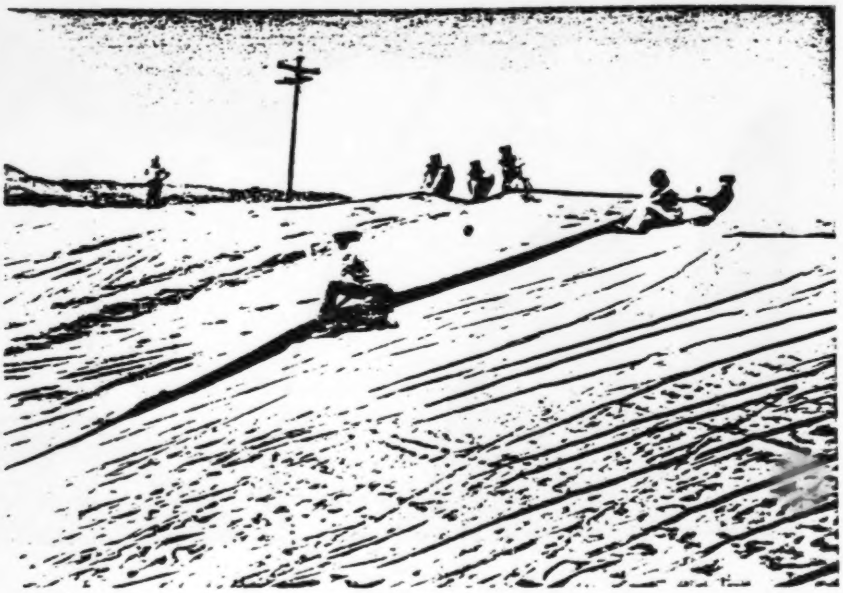

Figure IV-12. Each panel must be pulled smooth, leaving enough slack to accommodate anticipated shrinkage due to temperature changes.

are bodied solvent, heat, or contact adhesive. Solvent and contact adhesive systems are the most prevalent. The installation contractor should use the manufacturer's recommended procedure.

The integrity of the field seam is determined by many factors. The most important factor is that the adhesive system used must be compatible with the liner material and suitable for use under actual field conditions. As previously indicated, the liner manufacturers or installers have adhesive systems that work best for the products they make or work with. These systems normally have limitations with regard to temperature. Most adhesive systems work best at temperatures greater than 60°F.

Another important factor in field seam integrity is that the surfaces to be seamed are clean and dry when the field seams are made. The presence of any moisture can interfere with the curing and bonding characteristics of the adhesive used. The presence of any dirt or foreign material can jeopardize the seam strength and provide a path for fluid to migrate through the seam.

Since pressure must be applied to a seam after the adhesive has been applied, the liner ideally should rest on a dry, hard, and flat surface for rolling Many installers use a board such as described in Section 2 of this appendix. This board is placed underneath the overlap of the liner material. Overlaps can be anywhere from 4 to 12 inches wide, depending on the type of material and the conditions under which seaming takes place. Once the board is placed

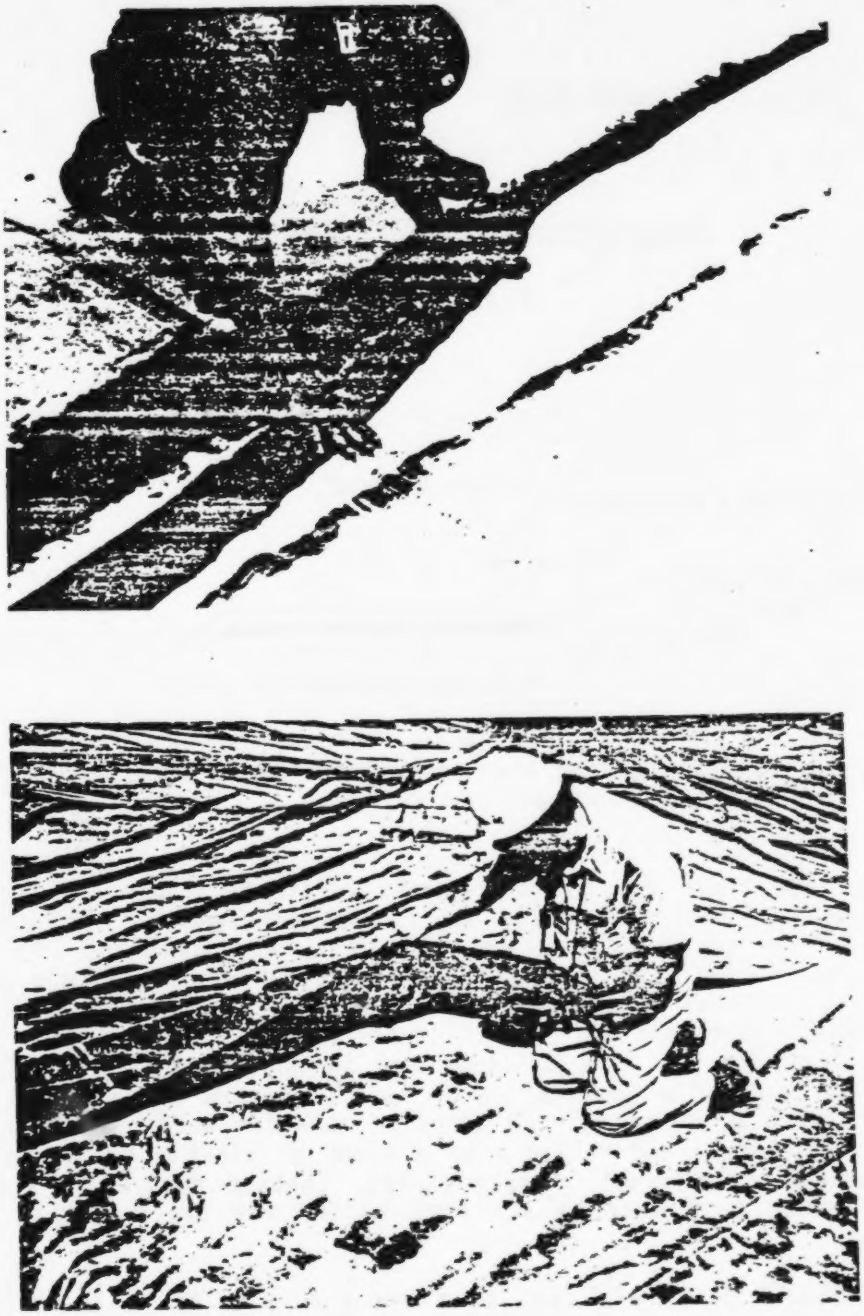

Figure IV-13. Sufficient seam overlap must be maintained. Manufacturers usually specify minimum overlap for field seams.

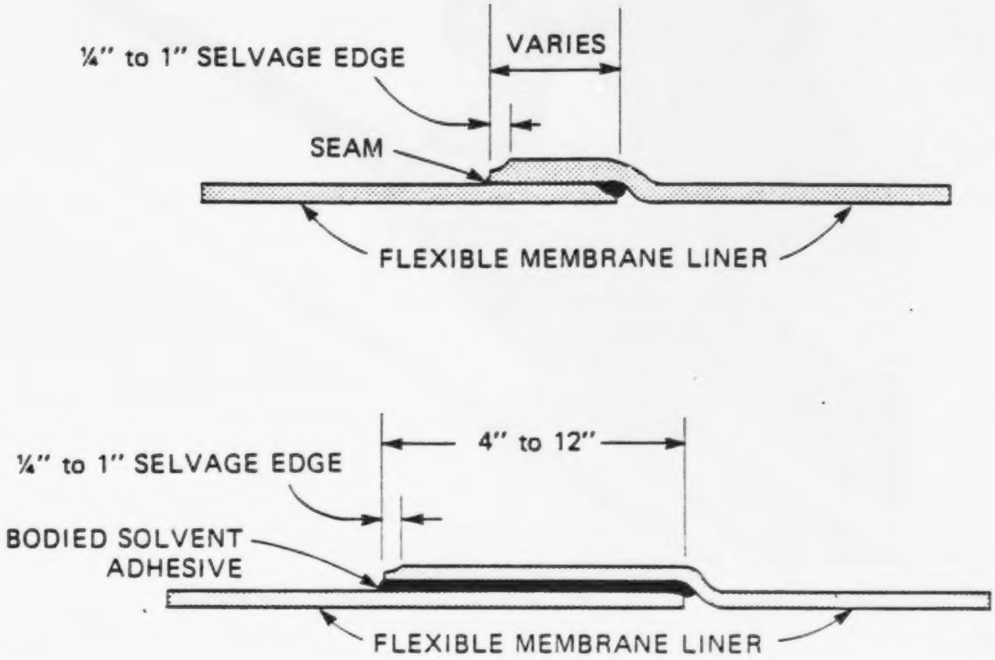

Figure IV-14 Typical factory seam (above) and field seam lap jointed. (From Small, 1980).

underneath the liner and the overlap is sufficient, then the top liner material should be peeled back and the surface prepared for the adhesive (Fig. IV-15). In the case of some liner materials, e.g. EPDM and CSPE, a surface cure must be removed with a solvent wash prior to seaming. Field crews should have suitable gloves to prevent skin irritation from the solvents (Figure IV-16). Respirators and eye protection may also be required. Once the surface cure has been removed, the adhesive can be applied to the liner material. Figure IV-17 shows the application of both a solvent and a contact adhesive. Generally, with a bodied solvent adhesive, the two surfaces should be placed together immediately and rolled with a steel or plastic roller perpendicular to the edge of the panel (Figure IV-18). Contact adhesive systems require that a certain tackiness be achieved before the two surfaces are placed together.

The crew should be careful not to allow any wrinkles to occur in the seam (Figure IV-19). All surfaces should be flat and rolled. It is important, whatever adhesive system is used, that the adhesive be applied uniformly. Field seaming should normally begin at the center of a panel and continue to each end of the seam. This minimizes large wrinkles which could occur if seaming began at one end or the other. In all cases, the adhesive system to be used by the field seaming crew should be that recommended by the manufacturer or a suitable substitute approved for a specific job.

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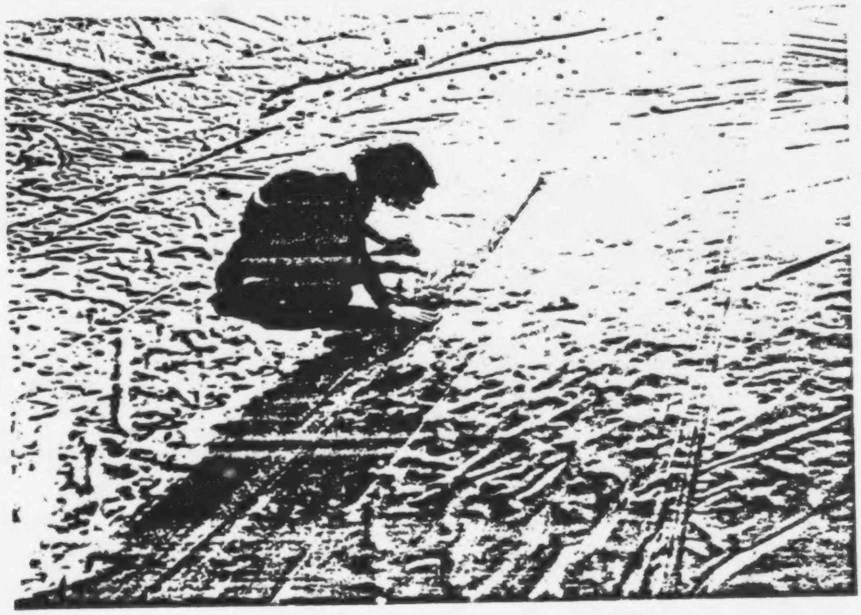


Figure IV-15. The surfaces to be seamed must be cleaned to remove dirt. Cleaning is usually accomplished with a solvent.

Figure IV-16. Seaming crews working with solvents are advised to use gloves for protection.

Generally, panels are placed so that field seams will run perpendicular to the toe of the slopes; that is, the seams will run up and down rather than along the side slopes. A good rule of thumb is always to place seams vertically on side slopes where possible without decreasing panel size or increasing field seaming. This practice minimizes stress on uncured field seams.

Installation of liner materials and field seaming during adverse weather conditions require special considerations with respect to adhesive systems and temperature limitations, e.g. 50°C is considered to be a minimum for most materials. This is particularly true with the thermoplastic materials since their properties change with temperature. Temperature also affects the rate that solvents will evaporate and the rate that seams become strong. Most adhesive systems work best when the temperature of the liner material itself is above 60°F. When ambient temperatures are below 60°F and a solvent adhesive system is being used, heat guns can provide an effective means to help bring the temperature of the liner material up to ideal conditions. Extreme caution must be exercised when using heat guns around flammable solvents, which may ignite, and chlorinated solvents which may generate the toxic gas, phosgene.

Cold weather seaming requires that the field crew exercise caution when making seams to assure that the temperature of the liner material reaches minimum acceptable conditions. A cold weather contact adhesive is sometimes used. Field seaming during precipitation should be avoided.

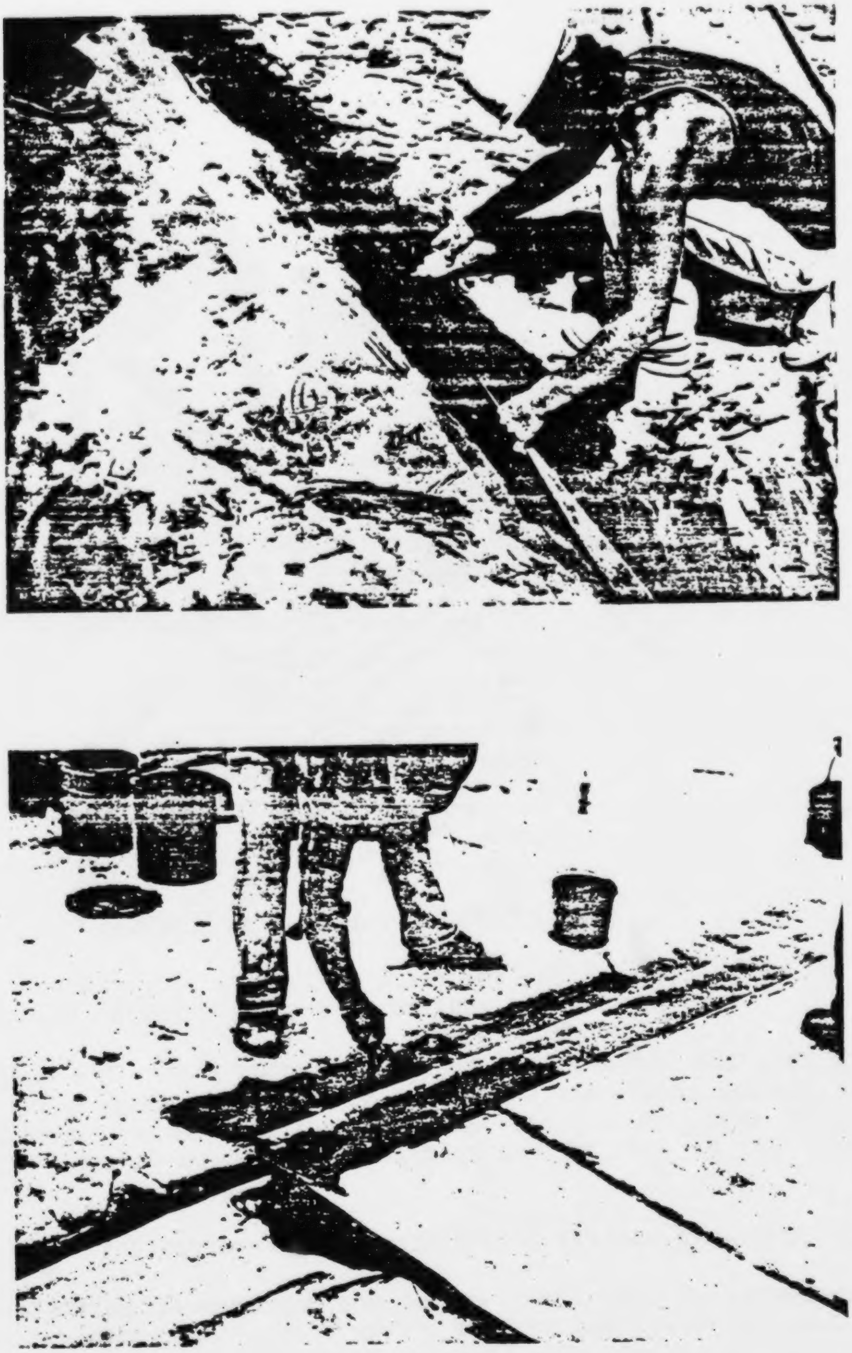


Figure IV-17. Field seaming. Adhesives are applied to the liner materials.

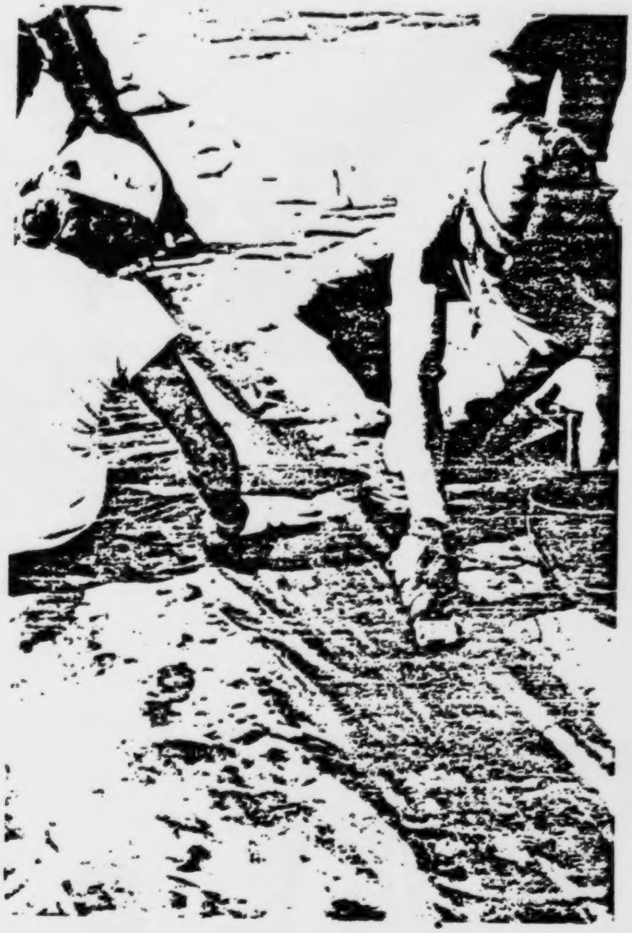


Figure IV-18. Rolling the seam. After the proper adhesive has been applied, the seam is rolled smooth.

Depending upon the location and the weather conditions, the number of panels placed in one day should not exceed the number which can be seamed in one day. This assures that, should bad weather conditions occur overnight, unseamed panels will not be left on the subgrade, subject to damage, especially from wind.

IV.6 Anchoring/Sealing Around Structures/Penetrations

Proper anchoring of the liner around the impoundment perimeter as well as conscientious tailoring and sealing of the liner around penetrating structures are essential to satisfactory liner performance. Generally, in cut-and-fill type impoundments, the liner material is anchored at the top of the dike or berm one of two ways: (1) using the trench-and-backfill method (Figure IV-20), or (2) anchoring to a concrete structure. The trench-and-backfill method seems to be recommended most often by liner manufacturers, probably due

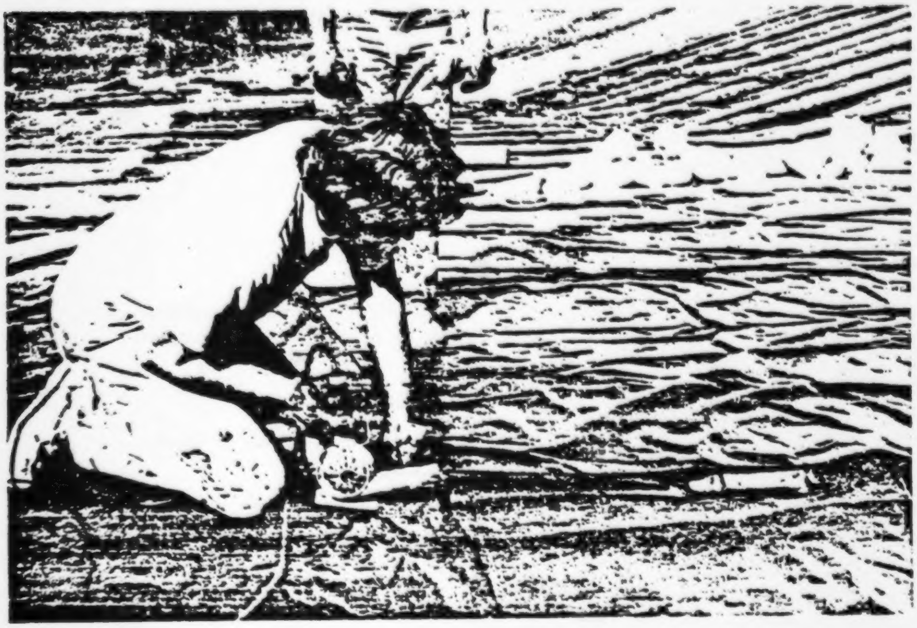


Figure IV-19. Repairing a wrinkle at the seams. The wrinkle is first preheated with a heat gun (top); after applying adhesive, the wrinkle is folded; the wrinkle has been rolled smooth and washed with a solvent; a patch is applied as a final step (bottom). Thicker sheeting, e.g. 45 mil, may require slitting and use of a cover strip.

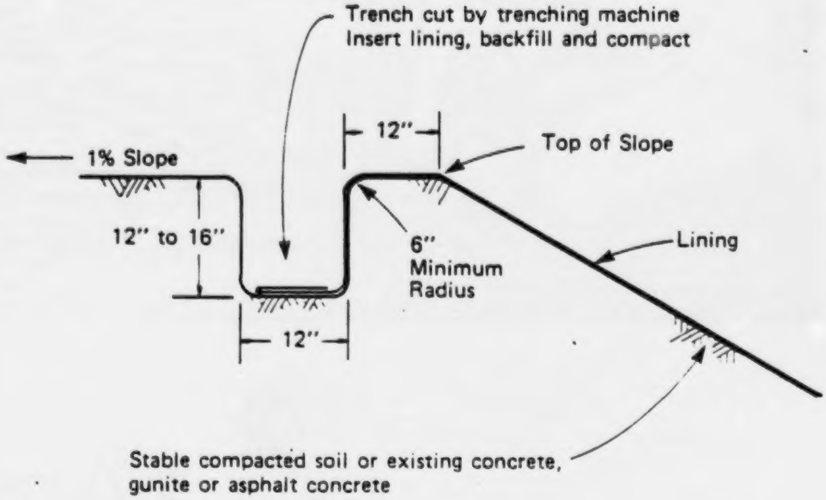

Trench cut by trenching machine
Insert lining, backfill and compact
12"
Top of Slope
1% Slope
12" to 16"
6"
Minimum
Radius
Lining
12"
Stable compacted soil or existing concrete,
gunite or asphalt concrete

Figure IV-20. Trench and backfill design for anchoring the perimeter of a membrane liner at the top of the pond sidewalls (Kays, 1977).

to its simplicity and economy. Excavation of the anchor trench in preparation for laying the liner is usually accomplished with a trenching machine such as a ditch witch or by using the blade of a bulldozer tilted at an angle. The latter method is considered to be less desirable. Dirt from the excavation should be spread away from the pit and smoothed to facilitate unrolling and spotting of panels.

Before opening and spotting the panels, provisions should be made for temporarily securing the edges of the liner panels in the anchor trench while the seaming takes place. After the seaming crew has completed the seams for a particular panel, the trench is backfilled with earth that was excavated from the trench. The trench should not be backfilled until after the panels have been seamed so that panels can be aligned and stretched, if necessary, for wrinkle-free seaming. If the trench (and the edge of the liner) is to be capped with concrete curbing, it is desirable to position reinforcing rods vertically in the trench prior to backfilling. These reinforcing rods serve to hold the liner in place while the seaming is done.

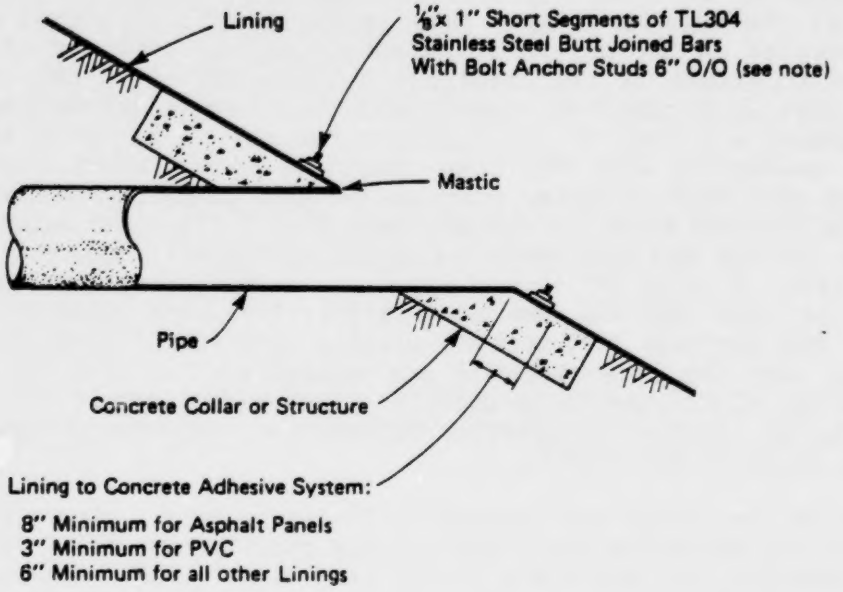
The perimeter of the liner may also be anchored to a concrete structure along the top of the berm or dike. This is usually accomplished with anchor bolts embedded in the concrete and batten strips composed of a material resistant to attack by the chemical(s) to be stored in the impoundment. Concrete that is to come into contact with the liner should have rounded edges and be smooth and free of all curing compounds to minimize abrasion and chemical interaction with the liner material. Anchor bolts should be positioned not more than 12 inches apart on centers. Concrete adhesive is applied in a strip (minimum width 3-6 inches, depending on the liner material) between the liner and the concrete where the batten strips will compress the liner to the concrete. A strip of lining material (chafer strip) may be sandwiched between the liner and the concrete wherever the liner material contacts an angle in the concrete structure to prevent abrasion. The batten strips are positioned over the liner material and secured with washers and nuts to the anchor bolts. Mastic should be used to effect a seal around the edge of the liner material. Several alternative methods for anchoring to concrete structures are shown in Kays (1977).

Depending on the design and purpose of the impoundment, one or more types of structures may penetrate the liner. These penetrations could include inlet, outlet, overflow, or mud drain pipes; gas vents; level indicating devices; emergency spill systems; pipe supports; or aeration systems. Penetrations may occur in the bottom or through one of the sidewalls, depending upon their function. Because tailoring and sealing the liner around structures can be difficult and offers a possibility for failure of the liner, several manufacturers recommend that over-the-liner pipe placement be used wherever possible. This design facilitates future repairs or maintenance to the piping system.

When penetrations through the liner are necessary, most manufacturers recommend specific materials and procedures to be used to establish an effective seal around the various types of penetrations. Proper design of the penetrations and selection of an adhesive material that is compatible with the liner are important factors to be considered relative to expected liner performance. For instance, some liner materials are not easily sealed to concrete. Selection of alternative materials may be required. Other materials, on the other hand, may offer optimal conditions for obtaining a good seal; for example, PVC liner can be effectively sealed to PVC pipe using the appropriate solvent to meld the materials together.

Most manufacturers offer standardized engineering designs for (a) seals made in the plane of the liner, and (b) boots to be used around penetrations. If inlet or outlet pipes are introduced into the impoundment through a concrete structure, the seal can be made in the plane of the liner. An example of this type of seal is presented in Figure IV-21. Here again, a special liner-to-concrete adhesive system is used that is designed for each liner material. Anchor bolts embedded in the concrete and batten strips of stainless steel should be used to secure the liner to the concrete. Mastic should be used around the edges of the liner material to effect a complete seal.

Typically, specialized features such as pipe boots or shrouds are fabricated at the manufacturing facility to design specifications, although they can sometimes be prepared in the field by experienced personnel. Where reinforced

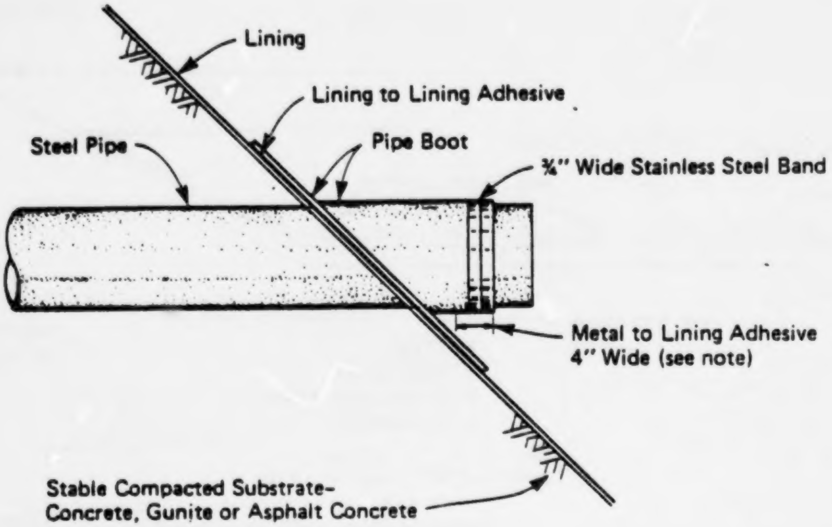

Lining
1/8" x 1" Short Segments of TL304
Stainless Steel Butt Joined Bars
With Bolt Anchor Studs 6" O/O (see note)
Mastic
Pipe
Concrete Collar or Structure
Lining to Concrete Adhesive System:
8" Minimum for Asphalt Panels
3" Minimum for PVC
6" Minimum for all other Linings

NOTE:
For asphalt panel linings, percussion driven studs thru 2" min. diameter x 1/16" thick galvanized metal discs at 6" O/C encased in mastic may be substituted for anchor shown

Figure IV-21. A commonly used flange type seal around penetrations (Kays, 1977).

membrane liners are being installed, manufacturers sometimes recommend that boots be constructed of unreinforced liner of the same type as that being installed. This allows the slightly undersized boot to be stretched over the appurtenance to assure good physical contact and allows some expandability in case the adjacent liner stretches due to settling. The boot is slipped over the pipe after the main piece of the liner has been cut and fitted around the base of the pipe. The proper adhesive is applied between the pipe and boot and a stainless steel band is placed around the boot where the adhesive has been applied between the pipe and boot. The base of the boot is seamed to the main part of the liner using the same adhesive system and methods used to make the field seams. Boots should be checked prior to installation to insure that the angle of intersection with the base is consistent with the angle created between the pipe and subgrade. An example of a seal created through the use of a pipe boot is presented in Figure IV-22.

It is important to assure that no "bridging" occurs in the liner material where angles are formed by the subgrade. Bridging is the condition that exists when the liner extends from one side of an angle to the other, leaving


Lining
Lining to Lining Adhesive
Steel Pipe
Pipe Boot
¾" Wide Stainless Steel Band
Metal to Lining Adhesive
4" Wide (see note)
Stable Compacted Substrate-
Concrete, Gunite or Asphalt Concrete

NOTE:
Clean pipe thoroughly at area of adhesive application

Figure IV-22. An example of a technique for sealing around penetrations using the boot type method (Kays, 1977).

a void beneath the liner at the apex of the angle. Bridging occurs most often at penetrations and where steep sidewalls meet the bottom of the impoundment. Particular attention should be directed to keeping the liner in contact with the subgrade at these locations and that it be in a relaxed condition. It is also important to be sure that compaction of the subgrade in these areas meets design specifications to avoid localized stressing of the liner material or seams.

Special considerations must be given to instances where dynamic head is going to be dissipated onto the liner. This would occur, for example, at an inlet structure where water will be flowing into the impoundment. Generally, a splash pad should be constructed by placing one or more additional layers of liner at the point of impact to help absorb energy resulting from the inflow of water. A concrete pad or a filter fabric geotextile may also be used under the liner to insure further mechanical stability (Figure IV-23). If water is to be discharged into an impoundment, often the design will specify a sluice type trough which can also be constructed out of liner material and placed on top of the main liner (Figure IV-24). This will help prevent

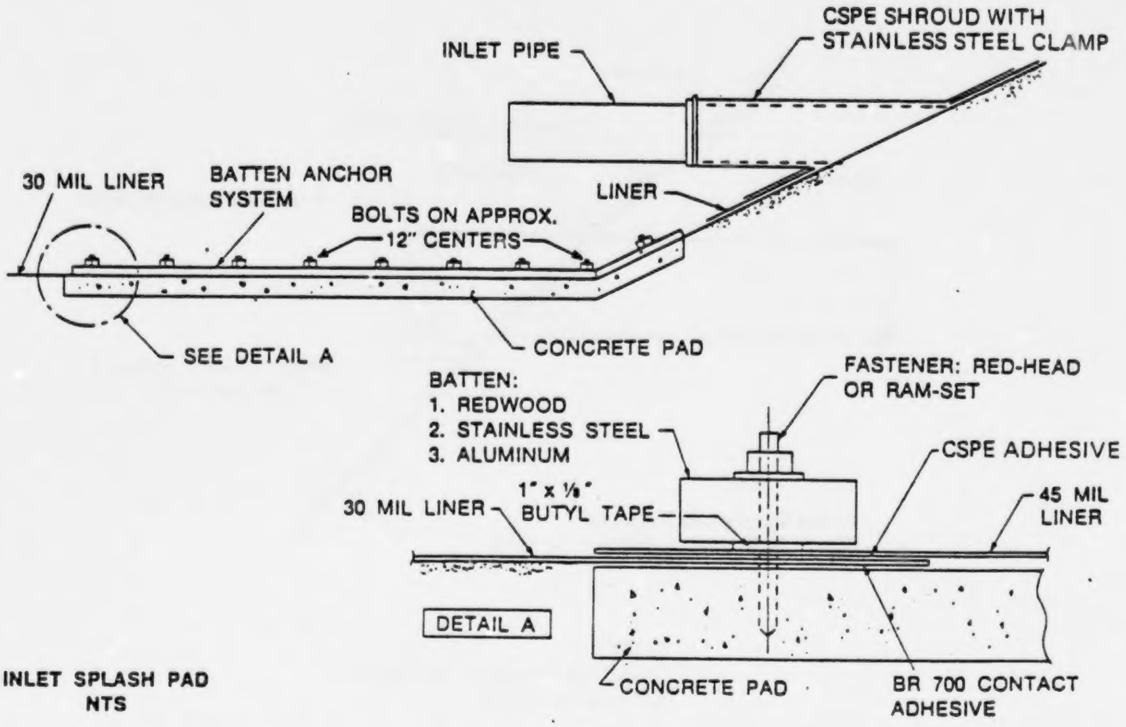

CSPE SHROUD WITH
STAINLESS STEEL CLAMP
INLET PIPE
30 MIL LINER
BATTEN ANCHOR SYSTEM
LINER
BOLTS ON APPROX. 12" CENTERS
SEE DETAIL A
CONCRETE PAD
FASTENER: RED-HEAD OR RAM-SET
BATTEN:
1. REDWOOD
2. STAINLESS STEEL
3. ALUMINUM
CSPE ADHESIVE
1" x 1/8" BUTYL TAPE
30 MIL LINER
45 MIL LINER
DETAIL A
INLET SPLASH PAD
NTS
CONCRETE PAD
BR 700 CONTACT ADHESIVE

Figure IV-23. Splash pad construction using a concrete subbase. (Source: Burke Rubber Company)

damage to the main liner resulting from any abrasive material which might be present in the water discharged into the facility.

If gases are expected to accumulate under the liner or large expanses of the sides of an impoundment will be exposed to high velocity winds, gas vents should be installed. Gas vents should be located just below the berm on the freeboard area.

If an aeration system is part of the facility design, appropriate precautions should be taken to insure that the liner surrounding the structure remains in position. This is usually accomplished by using a mooring pad placed on top of the liner for a floating aerator. The mooring pad also prevents mechanical damage to the liner immediately adjacent to the aerator. It is recommended that an additional layer of liner material be placed between the mooring pad and the main part of the liner. When a fixed aerator is used, the liner material may cover the foundation pad and an additional pad can be poured over the liner. Here again, an additional layer of liner material is sandwiched between the pad and liner. Permanent anchors should be placed ten feet apart in a circle approximately 20 feet from the base of the aerator to prevent the liner material from being lifted from the subgrade. Figure IV-25 shows some typical design details for aeration structures.

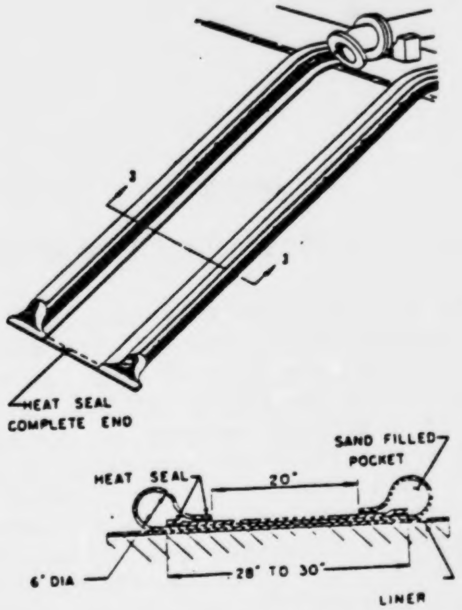

3
3
HEAT SEAL
COMPLETE END
SAND FILLED
POCKET
HEAT SEAL
20"
6" DIA
28" TO 30"
LINER

Figure IV-24. Sluice type trough constructed of liner material. The easiest method of placing inlet and outlet pipes into a membrane lined lagoon is over the top of the berms, using a protective liner to contain the discharge, thus protecting the main liner. The fewer protrusions that are designed into a lining, the easier it is to install and maintain both the liner and the piping. A double layer of liner material over the liner at the inlet may also be sufficient, as opposed to the prefabricated trough illustrated (Source: B. F. Goodrich).

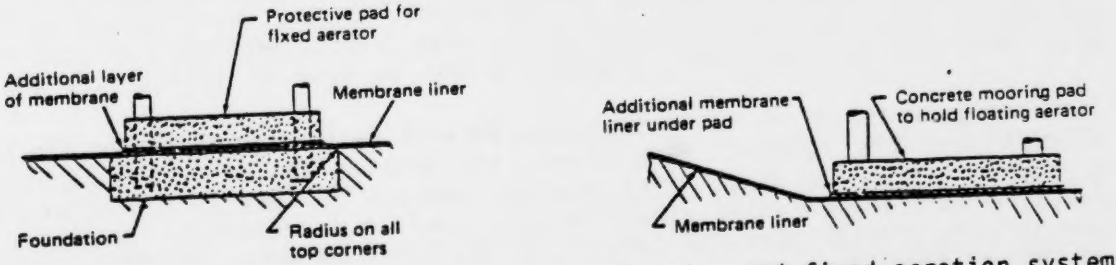

Protective pad for
fixed aerator
Additional layer
of membrane
Membrane liner
Foundation
Radius on all
top corners
Additional membrane
liner under pad
Concrete mooring pad
to hold floating aerator
Membrane liner

Figure IV-25. Typical design details for floating and fixed aeration systems (Kays, 1977).

Personnel reviewing the design or performing quality control functions for a liner installation should be familiar with the liner manufacturer's recommendations regarding all facets of the material's use and installation. This includes everything from the liner's compatibility with the material being stored to recommendations regarding specific adhesive systems and special seaming instructions around penetrations.

Note: See Chapter 5 for References.

APPENDIX V

LEACHATE COLLECTION SYSTEM NETWORK

A leachate collection system generally consists of strategically placed perforated drain pipe bedded and backfilled with drain rock. The pipe can be installed in a trench or on the base of the landfill. The system can be installed either around the perimeter of the landfill or underneath the landfill in the form of a complex network of collection pipes. The latter is utilized when the areas involved are very large and/or the allowable head buildup is small (see Section 5.6.3, "Transmissivity"). The collection system is drained to a sump or a series of sumps from which the leachate is withdrawn. This Appendix discusses the layout, sizing, installation, and selection of pipe material for leachate collection systems. A series of charts and tables are presented for use in the design and analysis of such systems.

V.1 Flow Capacity

As indicated in Chapter 5, the spacing of leachate collection pipes will influence the maximum head of leachate on the base of the fill, given a uniform rate of leachate percolation to a saturated fill and the permeability of the medium through which the leachate is withdrawn. Figure 5-26 can be used to select the required pipe spacing given an allowable leachate head over the base of the landfill. Figure V-1 shows the flow that must be carried in a collection pipe for various percolation rates and collection pipe spacings. With the required flow known, Figure V-2 can be used to select pipe sizes.

The configuration of the collection pipe network varies, depending on the head allowed over the landfill base liner: the greater the allowable head, the greater the pipe spacing. For maximum control of lateral migration, the leachate collection system should extend completely around the perimeter of the site to provide absolute control of the level to which leachate can rise on this critical boundary.

An interior grid system becomes necessary if the leachate head on the base of the fill must not exceed a specified value. The slopes and spacing of the interior grid pipes are controlled largely by a base slope of a minimum of two percent. Placement of a layer of permeable material over the base of the fill, coupled with the use of an interior collection pipe grid, may be necessary in extreme cases where the development of a leachate head cannot be tolerated.

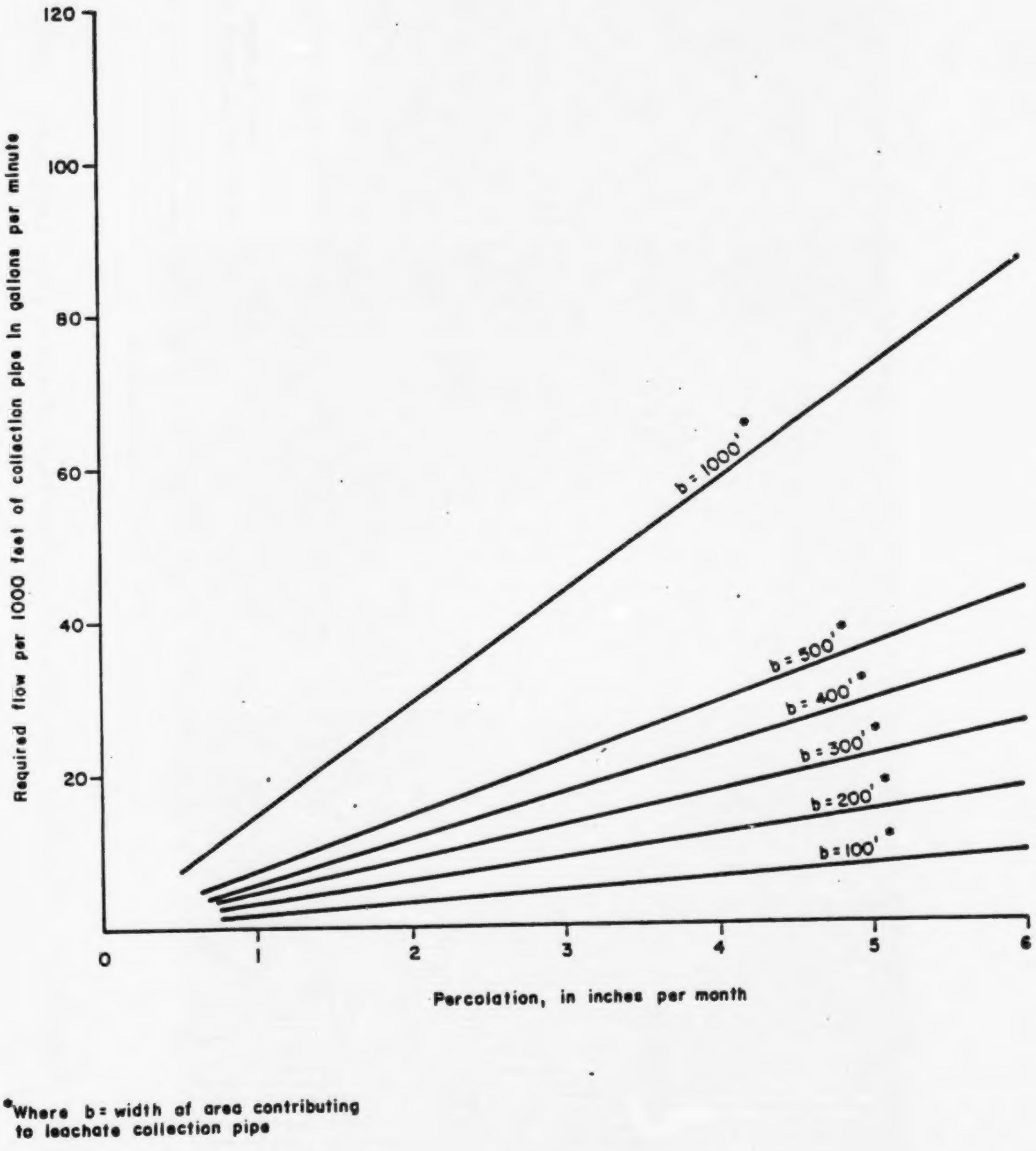


Figure V-1. Required capacity of leachate collection pipe.

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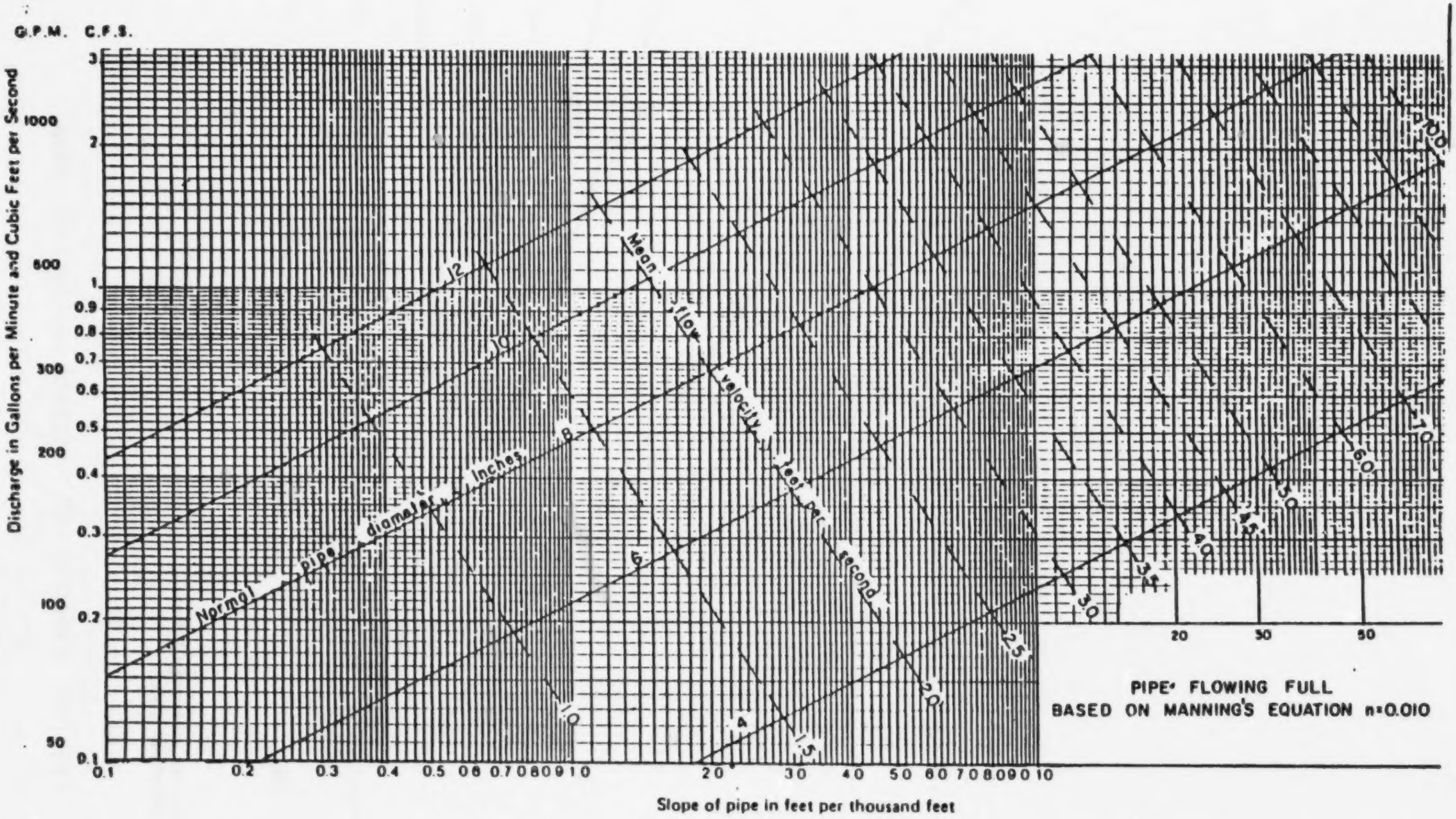


Figure V-2. Sizing of leachate collection pipe (Plastic Pipe Institute, 1975).

V.2 Structural Stability of Pipe

V.2.1 Introduction

Pipes installed at the base of a landfill to collect and conduct leachate to withdrawal wells can be subjected to high loading of waste fills, which can rise several hundred feet above the pipe.

Leachate collection pipes beneath landfills generally are installed in one of two conditions: (1) a trench condition or (2) a positive projecting condition. These installation conditions are shown on Figure V-3. In the analysis of the structural stability of a pipe under the imposed loading, the pipe is considered either a rigid or flexible conduit. Examples of rigid conduits are concrete and cast iron pipe. Plastic and fiberglass pipes are examples of flexible pipe. Because the landfill environment is highly corrosive, pipe materials generally selected for use in leachate control systems are plastic or fiberglass due to their relatively inert properties with respect to typical municipal leachate. This section discusses the structural stability of flexible pipe in landfill applications.

V.2.2 Loads Acting on Pipe

Loads are determined for one of two conditions: a trench condition or a positive projecting condition.

V.2.2.1 Trench Condition (Figure V-3)

This condition is assumed to exist whenever the top of the pipe is located below the ground surface. Load on the pipe is caused by both the waste fill and the trench backfill. These two components of the total vertical pressure on the pipe are computed separately and then added to obtain the total vertical pressure acting on the top of the pipe. The refuse fill is assumed to develop a uniform surcharge pressure, q_f, at the base of the refuse. The magnitude of q_f is given by the expression:

$$q_f = (\omega_f)(H_f)$$

where:

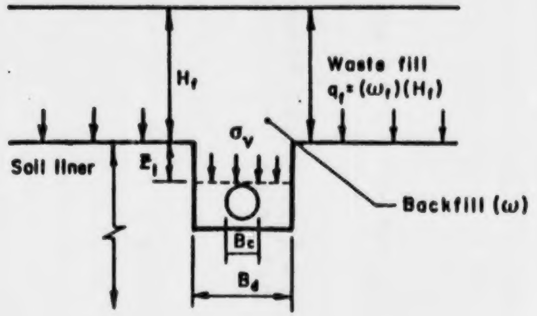
q_f = vertical pressure at the base of the refuse due to waste fill (lbs/sq ft)

ω_f = unit weight of the waste fill (lb g/cu ft); values range between 45 and 65 for municipal waste with soil cover

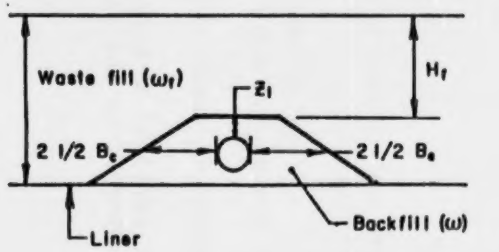
H_f = height of waste fill (ft).

The value of the vertical pressure at the top of the pipe due to the waste fill may be determined from the following equation:

$$\sigma_{v1} = q_f \, C_{\mu s}$$


H_f
Waste fill
q_f = (ω_f)(H_f)
σ_v
Soil liner
z_1
Backfill (ω)
B_c
B_d

a) TRENCH CONDITION


Waste fill (ω_f)
z_1
H_f
2 1/2 B_c
2 1/2 B_c
Backfill (ω)
Liner

b) PROJECTING CONDITION

Equations for determining the vertical pressure acting on the pipe:

For TRENCH CONDITION:

$$\sigma_v = B_d \omega C_D + q_f C_{u.s.}$$

Where: $$C_D = \frac{\left[1 - e^{-2K\mu(z/B_d)}\right]}{2K\mu}$$

$$C_{u.s.} = e^{-2K\mu(z/B_d)}$$

$$W = \sigma_v B_c$$

For PROJECTING CONDITION:

$$\sigma_v = (\omega_f)(H_f) + \omega z_1$$

DEFINITIONS:

ω = unit weight of backfill

W_f = unit weight of waste fill

H_f = height of waste fill

q_f = vertical pressure at the bottom of the waste fill

σ_v = vertical pressure at the top of the pipe

W = force per unit length of pipe

z_1 = height of backfill above the pipe

B_d = width of trench

B_c = outside diameter of pipe

K = lateral pressure coefficient of backfill

μ = coefficient of friction between backfill and the walls

Figure V-3. Pipe installation - conditions and loading (Clarke, 1968).

The term $C_{\mu s}$, a load coefficient, is a function of the ratio of the depth of the trench, $\bar{Z}$, (measured from the ground surface to the top of the pipe) to the width of the trench, B_d, and of the friction between the backfill and the sides of the trench. It may be calculated from the following equation or obtained from Figure V-4.

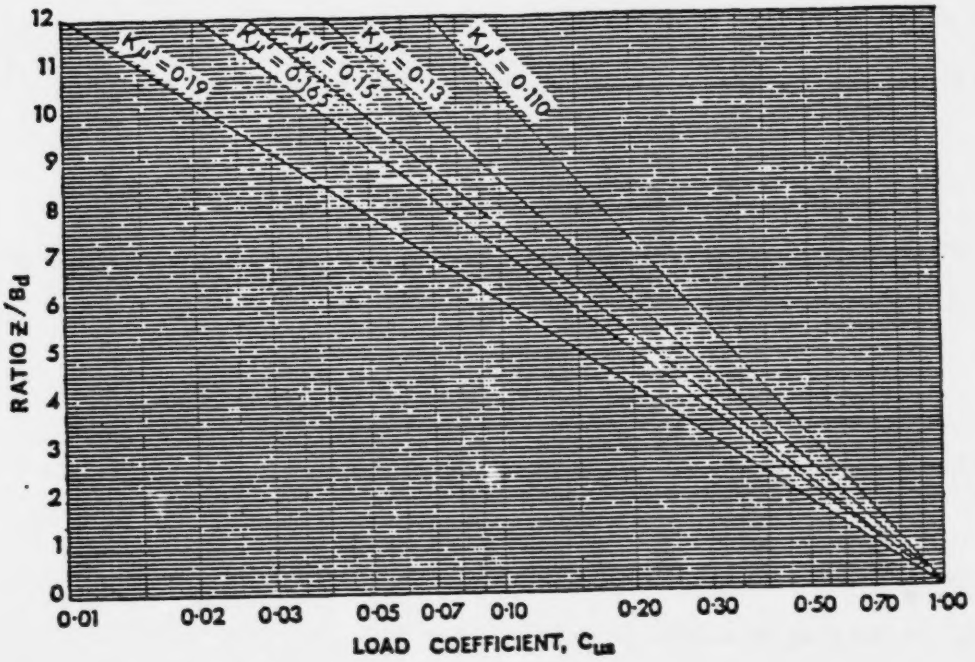
$$C_{\mu s} = e^{-2K\mu'(\bar{Z}/B_d)}$$

where: K = lateral pressure coefficient of the trench backfill.

μ' = coefficient of friction between backfill and the walls of the trench.

$\bar{Z}$ = depth of trench from original ground surface to top of pipe (ft)

B_d = width of trench at top of pipe (ft).



Values of load coefficient C_{us} (trench uniform surcharge)

Figure V-4. Projecting condition - pipe load coefficient (Clarke, 1968).

The product of $K\mu'$ is characteristic for a given combination of backfills in natural (in place) soil. Maximum values for typical soils are presented in ASCE Manual of Practice, No. 37. Those values of $K\mu'$ representing soils in which flexible pipes are likely to be installed are:

Type of soil	Maximum value of $K\mu'$
Sand and gravel	0.165
Saturated top soil	0.150
Clay	0.130
Saturated Clay	0.110

The value of the vertical pressure at the top of the pipe due to the trench backfill may be determined from the following equation developed by Marston:

$$\sigma_{v_2} = (B_d)(\omega)(C_d)$$

where: ω = unit weight of trench backfill (lbs/cu ft).

The term C_d is a load coefficient which is a function of the ratio Z/B_d and the friction between the backfill and sides of the trench. It may be computed from the following equation or obtained from Figure V-5.

$$C_d = \frac{1-e^{-2K\mu'(Z/B_d)}}{2K\mu'}$$

where the terms are as defined above.

The total vertical pressure is equal to:

$$\sigma_v = \sigma_{v_1} + \sigma_{v_2} = q_f\ C_{\mu s} + B_d\ \omega\ C_d.$$

The force per unit length of the pipe is equal to:

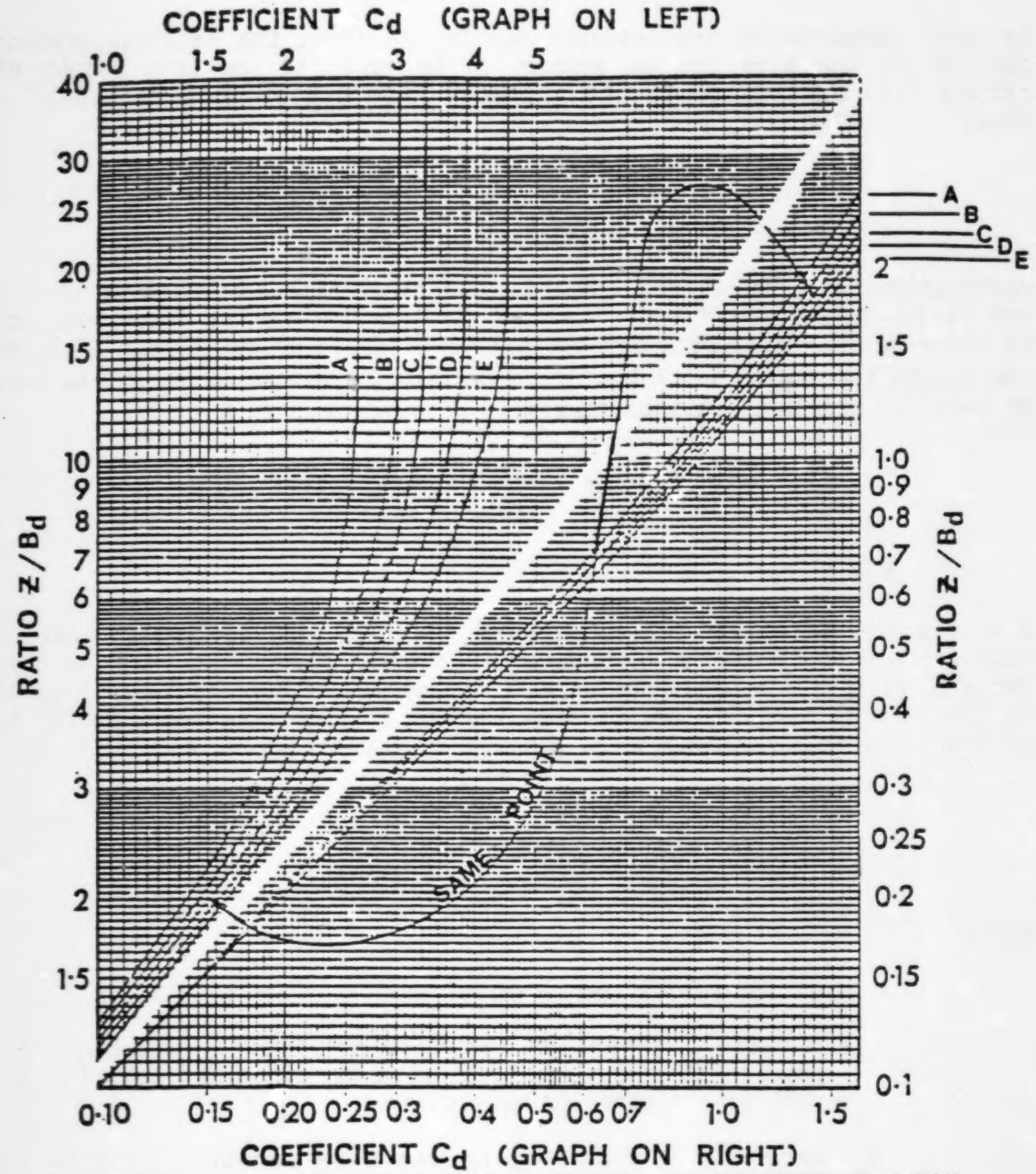
$$W = \sigma_v\ B_c$$

where: W = force per unit length of pipe

B_c = outside diameter of pipe

V.2.2.2 Positive Projecting Condition (Figure V-3)

This condition is assumed to exist whenever the top of the pipe is at or above the level of the refuse base. In this case, the load on the pipe can be assumed to be equal to the weight of a prism of overlying waste fill with a width B_c and height H_f plus the weight of a similar prism of gravel backfill above the pipe; because the pressure due to the gravel backfill typically will



A—C_d for $K\mu' = 0.19$, for granular materials without cohesion
B—C_d for $K\mu' = 0.165$ max. for sand and gravel
C—C_d for $K\mu' = 0.150$ max. for saturated top soil
D—C_d for $K\mu' = 0.130$ ordinary max. for clay
E—C_d for $K\mu' = 0.110$ max. for saturated clay

Values of load coefficient C_d (back fill)

Figure V-5. Trench Condition - Pipe Load Coefficient (Clarke, 1968).

be small compared to the pressure due to the fill, the vertical pressure on the top of the pipe can be assumed to be equal to the unit weight of the refuse fill multiplied by the distance from top of fill to top of pipe, thus:

$$\sigma_v = (\omega_f)(H_f).$$

V.2.2.3 Perforated Pipe

Perforations will reduce the effective length of pipe available to carry loads and resist deflection. The effect of perforations can be taken into account by using an increased load per nominal unit length of the pipe. If l_p equals the cumulative length in inches of perforations per foot of pipe, the increased vertical stress to be used equals:

$$(\sigma_v)_{design} = \frac{12}{12-l_p} \times (\sigma_v)_{actual}$$

V.2.3 Deflection

A well accepted formula for calculating flexible pipe deflection under earth loading is that developed by Spangler. This equation, also known as the Iowa formula, is presented together with suggested values for its various constants in the 1970 edition of the American Society of Civil Engineers (ASCE) Manual of Practice, No. 37, Chapter 9, Section E, Subsection 1, and is as follows:

$$\Delta y = D_e \frac{KWr^3}{EI + 0.061 E'r^3}$$

where:

Δy = horizontal and vertical deflection of the pipe (in)

D_e = a factor, generally taken at a conservative value of 1.5, compensating for the lag or time dependent behavior of the soil/pipe systems (dimensionless)

W = vertical load acting on the pipe per unit of pipe length (lb/in)

r = mean radius of the pipe (in)

E = modulus of elasticity of the pipe materials (psi)

E' = modulus of passive soil resistance (psi) (normally estimated to be 300 psi for soils of Proctor density of 65%, and 700 psi for soils of Proctor density of at least 90%)

K = bedding constant, reflecting the support the pipe receives from the bottom of the trench (dimensionless) (a conservative value generally taken 0.10)

I = moment of inertia of pipe wall per unit of length (in^4/in); for any round pipe, $I = t^3/12$ where t is the average thickness (in).

The equation can be rewritten to express pipe deflection as a decimal fraction of the pipe diameter, B_c, and to relate it to the vertical stress on the pipe as follows:

$$\frac{W}{B_c} = \sigma_v = \frac{(\Delta y)}{(B_c)}\left(\frac{EI + 0.061E'r^3}{D_e K r^3}\right).$$

Solutions to this equation are shown graphically in Fig. V-6 where the quantity $\sigma v/(\Delta y/B_c)$ has been plotted against the passive soil modulus E'. The relationship between $\sigma v/(\Delta y/B_c)$ and E' has been shown for four plastic pipes: 4 and 6-inch Schedule 40 and 4 and 6-inch Schedule 80 PVC pipe. In computing the quantity EI for these pipes, a reduced modulus was used to account for creep of the plastic pipe. A value equal to 142,000 psi was used to correspond to the modulus at 50 years under sustained loading (see Janson, 1974). Also shown is the relationship for EI=0. This would represent a relationship between $\sigma v/(\Delta y/B_c)$ and E' if the stiffness of the pipe is neglected.

In addition to using the chart to check the adequacy of a given pipe, the chart can be used to determine the necessary value of EI/r^3 which the pipe must have for given values of $\sigma max/(\Delta y/B_c)$ and E'. Although it is customary to use either 300 or 700 psi for the value of the modulus of passive soil resistance, it should be noted that the modulus of elasticity of a coarse grained soil (sand or gravel) increases with increasing pressure (or depth in the ground). Thus, it should be expected that the modulus of passive soil resistance also would increase with increasing pressure or depth of fill.

The term EI in Spangler's equation reflects the pipe's contribution to the total resistance to deflection under load offered by the pipe/soil system. This term, known as the pipe's Stiffness Factor, is related to the pipe's behavior under parallel plate loading as per ASTM D 2412, External Loading Properties of Plastic Pipe by Parallel Plate Loading, by the following expression:

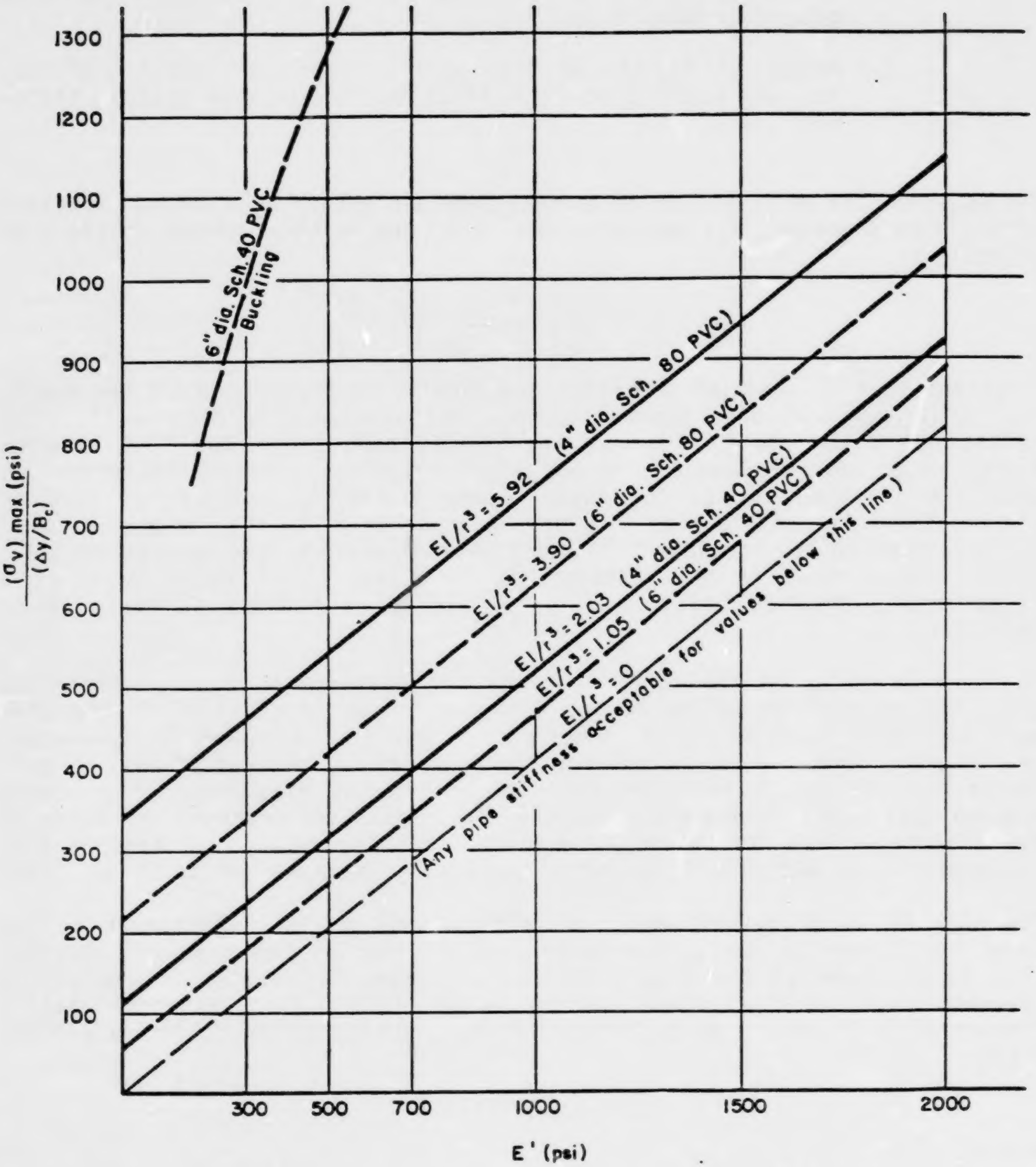
$$EI = 0.149r^3(F/\Delta y)$$

where:

E, I and r are as previously defined

F = the recorded load (lb/linear inch) required to produce a pipe deflection Δy

Δy = the pipe's deflection (in).



$$\frac{\sigma_v}{(\Delta y/B_c)} = \frac{\left[EI + 0.061\ E' r^3\right]^*}{D_e K\ r^3} \qquad \text{Assumed: } \left.\begin{matrix} D_e = 1.5 \\ K = 0.1 \end{matrix}\right\}^{**}$$

Figure V-6. Selection of Pipe Strength
* (ASCE, 1969)

Minimum values of the term $F/\Delta y$, called Pipe Stiffness, are set according to Pipe DR (dimension ratio) by the ASTM PVC Sewer Pipe Specifications D 3033 and D 3034. The DR represents the ratio of the pipe's average outside diameter to its minimum wall thickness. Thus, for each DR there is a corresponding minimum specified value of $F/\Delta y$.

The above expression for EI can be substituted into the previous equation for deflection to obtain the following:

$$\frac{\sigma_v}{(\Delta y/B_c)} = \frac{(0.149F/\Delta y) + 0.061E'}{D_e K}$$

Solutions to this equation can be made on a graph similar to Fig. V-6 where the quantity $\sigma v/(\Delta y/B_c)$ is plotted against the soil modulus E' for several values of $F/\Delta y$.

V.2.4 Buckling Capacity

The capacity of a buried plastic drain pipe to support vertical stresses may be limited by buckling. Estimates of the vertical stresses at which buckling of the 6-inch Schedule 40 PVC pipe (the most flexible of the four pipes shown) will occur are indicated by the curve in Fig. V-6. For the four pipes shown, buckling would not be a controlling factor. However, it could be a controlling factor, depending on the flexibility of the pipe and the modulus of passive soil resistance. Specific information for other sizes and pipe materials proposed for use in the collection system should be secured from the pipe manufacturer.

V.2.5 Compressive Strength

The capacity of the pipe to support vertical stresses may be influenced by the circumferential compressive strength of the pipe. The designer or reviewer should secure up-to-date information on circumferential compressive strength characteristics from the manufacturer of the type of pipe proposed for use.

V.2.6 Construction Loadings

A pipe correctly designed to withstand loading from a high fill can fail from loading received during construction. Although only a fraction of a stationary wheel or tracked vehicle load applied at the ground surface over a trench is transmitted to a pipe through the trench backfill, the percentage increases rapidly as the vertical distance between the loaded surface and the top of the pipe decreases. In addition, moving loads cause impact loading generally considered to have a 1.5 to 2.0 multiplier effect over stationary loading.

In general, equipment should not cross leachate collection drains installed in trenches with shallow cover or in projecting installations. When equipment must be routed across a drain, impact loading can be minimized by mounding material over the pipe to provide a vertical separation of 4 feet between the loaded surface and the top of the pipe.

V.2.7 Procedures for Selection of Pipe Strength

The procedures used to select the proper strength pipe are illustrated in the following examples:

Trench Installation (See Figures V-4 and V-7)

Given: $Z = 1'\text{-}8"$ $\quad H_f = 100$ feet waste fill

$B_d = 1'\text{-}6"$ $\quad \omega_f = 50$ pcf

$K_\mu' = 0.19$ $\quad \omega = 110$ pcf

pipe diameter = 4"

Determine: Required pipe strength/schedule.

Step 1 - Determine the maximum vertical pressure σ_v (psf) acting on the top of the pipe.

$$\frac{Z}{B_d} = \frac{1.67}{1.5} = 1.11 \qquad q_f = (\omega_f)H_f = 100\ (50) = 5000 \text{ psf}$$

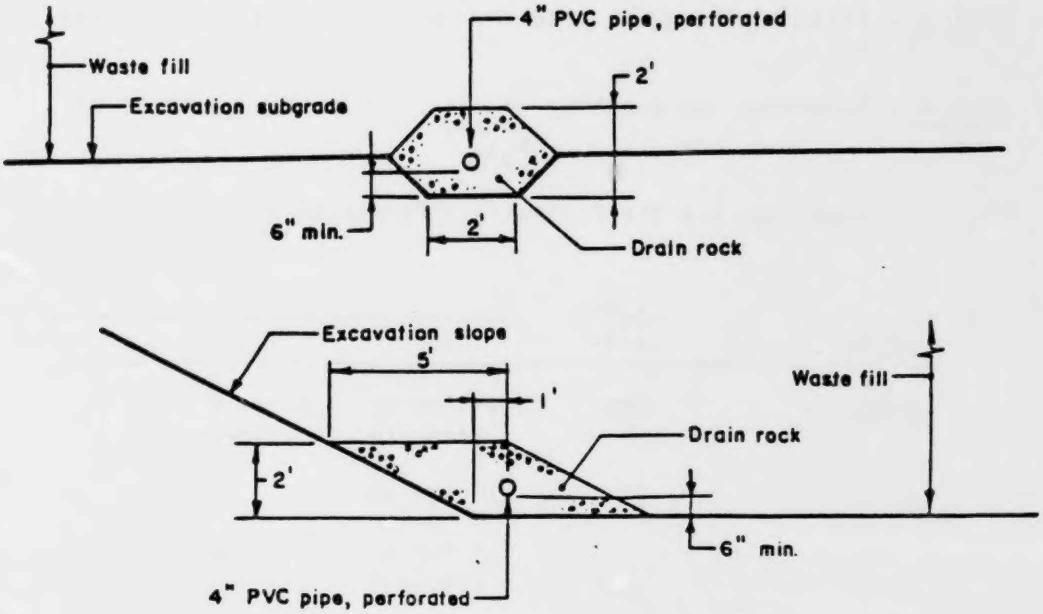
from Fig. V-4, $C_{\mu s} = 0.64$

Fig. V-5, $C_d = 0.9$

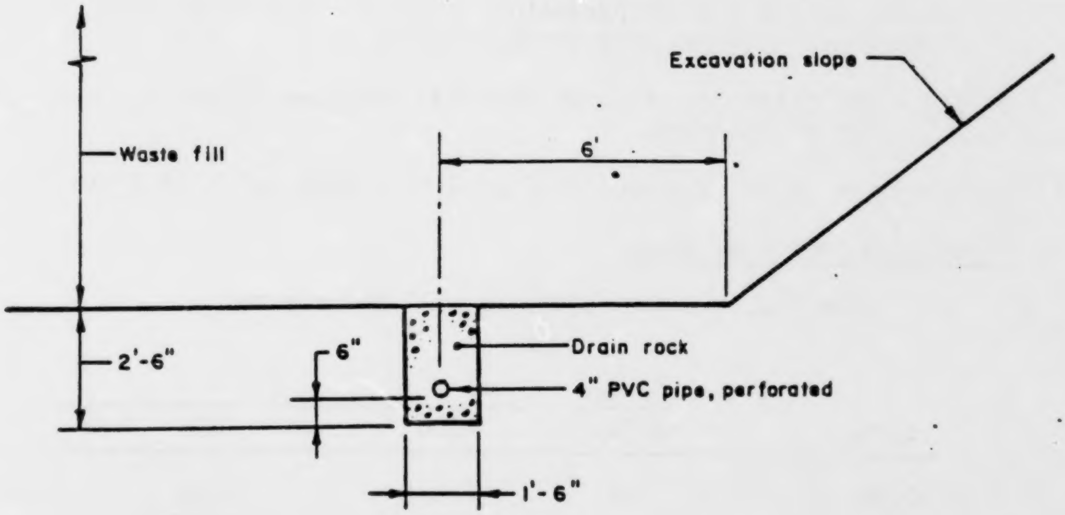
then; $\sigma_v = (\omega)(B_d)(C_d) + (q_f)(C_{\mu s})$

$= (110)(1.5)(0.9) + (5000)(0.64)$

$= 3348 \text{ psf} = 23.3 \text{ psi} = J_{v\ max}$


4" PVC pipe, perforated
Waste fill
Excavation subgrade
2'
6" min.
2'
Drain rock
Excavation slope
5'
1'
Waste fill
Drain rock
2'
6" min.
4" PVC pipe, perforated

PROJECTING INSTALLATIONS


Excavation slope
Waste fill
6'
Drain rock
2'-6"
6"
4" PVC pipe, perforated
1'-6"

TRENCH INSTALLATION

Figure V-7. Typical leachate collection drains.

Step 2 - Select the appropriate modulus of passive soil resistance E' (psi). For gravel bedding use 300 to 700 psi.

Step 3 - Select allowable pipe deflection ratio $\Delta y/B_c$. Use 0.05 to 0.1.

Step 4 - Determine the quantity $\dfrac{\sigma_{v\ max}}{\Delta y/B_c}$, where $\sigma_{v\ max}$ is in psi.

From Fig. V-6 the following information is obtained.

$\Delta y/B_c$	$\dfrac{\sigma_{v\ max}}{\Delta y/B_c}$	E' 300	E' 700
0.05	466	4" Sch 80 adequate	4" or 6" Sch 80 adequate
0.1	233	4" Sch 40 or 6" Sch 80 adequate	Any pipe

Positive Projecting Installation (See Figures V-3 and V-7)

Given: Z_1 = 6"; other parameters given as in example above
Determine: Required pipe strength/schedule

Step 1 - Determine the maximum vertical pressure σ_v(psf) acting on the top of the pipe.

$$\sigma_v = \omega_f H_f + \omega Z_1 = (50)(100) + (110)(0.5) = 5055 \text{ psf} = 35.1 \text{ psi} = J_{v\ max}$$

Steps 2, 3, and 4 as above

From Fig. V-6 the following will be obtained.

$\Delta y/B_c$	$\dfrac{\sigma_{v\ max}}{\Delta y/B_c}$	E' 300	E' 700
0.05	702	none acceptable	none acceptable
0.1	351	4" Sch 80 adequate	4" Sch 40 or 6" Sch 80 adequate

Note: See Chapter 5 for References.

APPENDIX VI

SYSTEM ANALYSIS AND OPTIMIZATION OF SOIL LINER DESIGN

The purpose of the design is to achieve a seepage below the liner, lower than a certain critical value, q_p. The analysis of the system can be done using different procedures. As an example, we will use the McWhorter and Nelson (1979) analysis. For convenience, we will preserve the nomenclature used by the authors. A schematic representation of the flow system is presented in Figure VI-1.

In the subsequent analysis, it is assumed that the geometry of the system is unchanged in time, i.e. the depth of the free waste fluid, y, the depth of the solid waste, D_t, and the depth of the underlying undisturbed soil, D_f, are given. The depth of the soil liner D_l is variable. The permeability of the solid waste, K_t, and the permeability of the isotropic, homogeneous underlying soil K_f are also given. The permeability of the soil liner K_l is variable and can be optimized vis-a-vis the depth of the soil liner D_l to result in a seepage rate lower than q_p. Other parameters which will be found in the analysis have the following meaning:

n = soil porosity, equal to volumetric moisture content when the soil is saturated.

θ_i = initial volumetric moisture content of the underlying soil.

h_d, θ_r, and λ = parameters experimentally found when determining the moisture characteristic curve (MCC). The MCC is the relation between the magnitude of suction applied and the equilibrium moisture content corresponding to the given negative head.

h_d = displacement pressure or air-entry pressure (negative). The threshold suction needed to break soil capillaries and allow water drainage. For most soils it is between -50 cm and -150 cm. The more clayey a soil the lower (the more negative) the h_d value.

θ_r = the residual moisture content on a MCC, the quasi-steady moisture-content encountered at large suctions. Often, to obtain this moisture content, the pressure has to be decreased to -15 atmospheres. θ_r is roughly the water stored in submicronic pores. It is normally in the range of 0.05 - 0.20 with the high values corresponding to clayey soils.

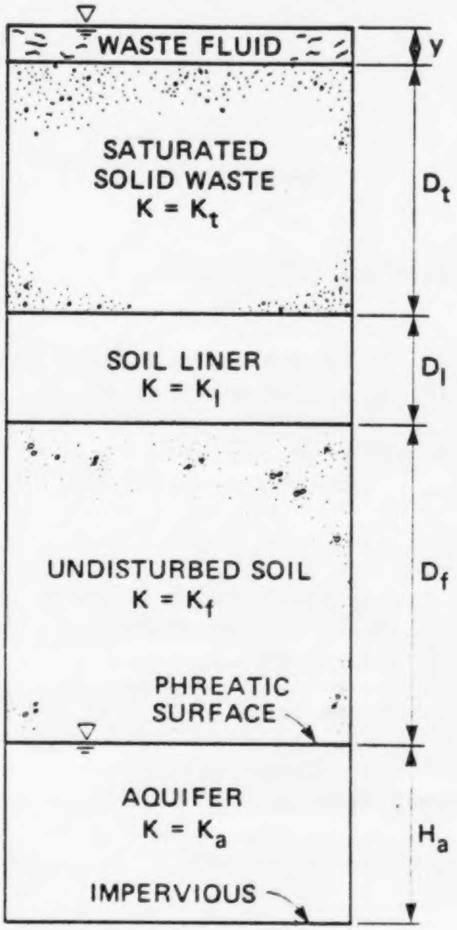

WASTE FLUID
y
SATURATED SOLID WASTE
K = K$_t$
D$_t$
SOIL LINER
K = K$_l$
D$_l$
UNDISTURBED SOIL
K = K$_f$
D$_f$
PHREATIC SURFACE
AQUIFER
K = K$_a$
H$_a$
IMPERVIOUS

Figure VI-1. Sketch of the flow system.

λ = a shape factor of the MCC. In the present analysis, it was assumed equal to unity.

h_c = effective capillary drive = $h_d \frac{(2+3\lambda)}{(1+3\lambda)}$. Since $\lambda = 1$ in this analysis, $h_c = 1.25\ h_d$.

The flow event is visualized as occurring in three stages:

Stage 1 - The infiltration of the fluid into the underlying, originally unsaturated soil. In the wetted region the same soil may or may not be fully saturated.

Stage 2 - This stage starts as soon as the wetting front reaches the groundwater or its capillary fringe and a groundwater mound is being formed. Stage 2 continues until the mound reaches the base of the liner.

Stage 3 - Saturated flow throughout the whole system.

It is clear that the slower every stage is developed the better suited the system is to confine wastes. If, for instance, Stage 3 is reached the success of the system in controling contamination will rely heavily on the ability of different strata (soil liner and underlying soil) to chemically bind the contaminants. If fresh waste fluid is continually added to the waste disposal site, the strata will reach their saturation. In the long run the system sketched in Figure VI-1 will have the same composition and concentration as the fresh waste fluid. The limiting concentration at a well will be a fraction of the fresh waste fluid concentration due to dilution by the incoming fresh groundwater stream.

At the present level of knowledge, we have to prevent the occurrence of Stage 3 and even Stage 2. Accordingly, we will analyze numerically some of the important parameters during the infiltration towards the groundwater (Stage 1).

Example of Numerical Analysis for Stage 1

The advancement of the wetting front between the soil liner/underlying soil interface and the original groundwater level can occur either as a saturated or as an unsaturated flow, depending on the geometry and flow properties of the traversed strata. For our purpose, the less saturated the flow the better, since the seepage rate is proportional to the degree of saturation. Consequently, it is important to design the system in such a way as to promote unsaturated flow during infiltration.

The flux across the sequence of solid waste-soil liner is given by the equation:

$$q = \frac{(y + D_t + D_l) - h_f}{\frac{D_t}{K_t} + \frac{D_l}{K_l}} \qquad (1)$$

where h_f is the pore-water pressure in the wetted underlying soil during flow with all other terms already defined (Equation 10, McWhorter and Nelson, 1979).

For unsaturated flow to occur, h_f has to be more negative than the air-entry pressure, h_d, i.e. $h_f < h_d$. Combining this condition with Equation 1 and $q=K_f$ results in: (Equation 14 in McWhorter and Nelson, 1979).

$$y + D_t + D_l - K_f \left[\frac{D_t}{K_t} + \frac{D_l}{K_l}\right] < h_d. \qquad (2)$$

Assuming the optimization of the system can be achieved by varying D_l and K_l, the depth and the permeability of the soil liner, and assuming the permeability of the underlying soil k_f is equal to 10^{-5} cm sec^{-1} and its air-entry pore-water pressure, h_d, is equal to -50 cm equivalent water, equation 2 becomes:

$$y + D_t - 10^{-5}\frac{(D_t)}{(K_t)} + 50 < 10^{-5}\frac{(D_l)}{(K_l)} - D_l \qquad (3)$$

The values of the left hand side of the inequality expressed in cm, are presented in Table VI-1 for different y, D_t, and K_t levels.

TABLE VI-1. LEFT HAND SIDE OF EQUATION 3, in cm

y, feet	D_t, feet	K_t (cm sec^{-1}) 10^{-4}	10^{-5}	10^{-6}
3	1	169	141	-133
	20	690	141	-5351
60	1	1906	1879	1604
	20	2428	1879	-3619

The right hand side of the inequality (Equation 3) expressed in cm, is presented in Table VI-2, for different combinations of k_l and D_l, the permeability and the depth of the soil liner.

TABLE VI-2. RIGHT HAND SIDE OF EQUATION 3, in cm.

K_l, cm sec^{-1}	D_l feet 1	6
10^{-6}	275	1,678
10^{-7}	3,023	18,123
10^{-8}	39,500	182,880

The condition of unsaturated flow $h_f < h_d$ is observed whenever the ratio of any figure from Table VI-1 to any figure from Table VI-2 is less than +1.

In Table VI-3, we present the system requirements which will generate the best observance of the condition $h_f<h_d$ and the worst observance of the same inequality.

TABLE VI-3. From Tables VI-1 and VI-2. THE BEST AND THE WORST COMBINATIONS OF PARAMETERS WHICH RESULT IN $h_f<<h_d$ AND $h_f>>h_d$, RESPECTIVELY

Parameters	Best Condition (Least Saturated Flow) $h_f<<h_d$	Worst Condition (Saturated Flow) $h_f>>h_d$
y, feet	3	60
D_t, feet	20	20
K_t, cm sec^{-1}	10^{-6}	10^{-4}
D_1, feet	6	1
K_1, cm sec^{-1}	10^{-8}	10^{-6}

The inspection of data in Tables VI-1, VI-2 and VI-3 should provide the designer with important clues regarding the choice of the relevant soil parameters D_1 and K_1. Moreover, in the real situation the variability of the parameters, in the left part of the inequality, i.e. Equation 3, is much smaller than the one considered in this example. Consequently, the figures in Table VI-1 will be closer to each other and the choice of a proper combination of D_1 and K_1 will thus be facilitated.

As an example, let us assume that the calculation of the left hand side term in Equation 3 resulted in a value equal to 1500. In Table VI-2 we find that the combination D_1 = six feet and $K_1 = 10^{-6}$ cm sec^{-1} satisfies our requirements, since $1678 > 1500$. The same requirements are satisfied by D_1 = two feet and a permeability K_1 = approximately 3×10^{-7} cm sec^{-1}. Considering both engineering and economic conditions, the designer will be able to optimize the two parameters.

Let us consider that the underlying soil has different properties than the ones assumed in the previous example. Suppose now $K_f = 10^{-6}$ cm sec^{-1} and $h_d = -150$ cm. This set of data should correspond to a more clayey soil. The new working equation generated for this case will be:

$$y + D_t - 10^{-6} \frac{(D_t)}{(K_t)} + 150 < 10^{-6} \frac{(D_1)}{(K_1)} - D_1 \qquad (4)$$

Paralleling the previous example, the values of the left hand side of the inequality are presented in Table VI-4.

TABLE VI-4. LEFT HAND SIDE OF EQUATION 4, in cm.

y feet	D_t feet	K_t (cm sec^{-1}) 10^{-4}	 10^{-5}	 10^{-6}
3	1	272	269	241
	20	845	790	241
60	1	2009	2006	1979
	20	2583	2528	1979

The right hand side of Equation 4 is presented in Table VI-5.

TABLE VI-5. RIGHT HAND SIDE OF EQUATION 4, in cm.

K_l cm sec^{-1}	D_l feet 1	 6
10^{-6}	0	0
10^{-7}	275	1,646
10^{-8}	3,020	18,107

The conclusion to be drawn from the first step of calculations is that unsaturated flow in the underlying soil is secured when the ratios K_l/K_f and K_t/K_f are very low. This can be seen from the inspection of Equation 2.

The condition of unsaturated flow $h_f<h_d$ is only the first step of the analysis. The result of this first step does not tell anything about the absolute value of the seepage through the system. To solve this aspect of the problem use is made of the relationship (Equation 16 from McWhorter and Nelson, 1979):

$$q = \frac{(y + D_t + D_l) - h_d\left[\frac{q}{K_f}\right]^{-1/(2+3\lambda)}}{\frac{D_t}{K_t} + \frac{D_l}{K_l}} \tag{5}$$

Before proceeding with the analysis the designer of the soil liner needs to know the q value (equivalent to q_p the permissible flux in the text, Section 5.2). Let us assume that the analysis of the system as a whole yielded a

q = 3 inches/year = 2.4×10^{-7} cm. sec^{-1}. Assuming, together with this figure, that the two important properties of the underlying soil are: $K_f = 10^{-5}$ cm sec^{-1} and $h_d = -50$ cm equivalent water, the resulting working equation becomes:

$$D_t \left(\frac{2.40 \times 10^{-7}}{K_t}\right) - y - D_t - 105.4 = D_l - D_l \left(\frac{2.4 \times 10^{-7}}{K_l}\right) \qquad (6)$$

The left hand side of Equation 6 can be calculated for different y, D_t, and K_t values. The results expressed in cm, are presented in Table VI-6.

TABLE VI-6. LEFT HAND SIDE OF EQUATION 6, in cm

y feet	D_t feet	K_t (cm sec^{-1}) 10^{-4}	10^{-5}	10^{-6}
3	1	-227	-227	-220
	20	-805	-792	-660
60	1	-1965	-1964	-1957
	20	-2542	-2529	-2398

The left hand side of Equation 6 and its right side have, for the chosen parameters, values between -200 and -2600 cm. If two particular values for the depth of the soil liner D_l are considered, one foot and six feet, the needed permeabilities of the soil liner K_l can be calculated. They are presented in Table VI-7.

TABLE VI-7. SOIL LINER PERMEABILITY K_l, REQUIRED TO RESTRICT THE FLUX AT q = 3"/YEAR, WHEN THE LEFT HAND SIDE OF EQUATION 6 TAKES VALUES BETWEEN -200 AND -2600, FOR TWO DEPTHS OF THE SOIL LINER, D_l.

Left hand side of Equation 6	D_l feet 1	6
-200	3.2×10^{-8}	1.1×10^{-7}
-600	1.2×10^{-8}	5.6×10^{-8}
-1000	7.1×10^{-9}	3.7×10^{-8}
-1400	5.1×10^{-9}	2.8×10^{-8}
-1800	4.0×10^{-9}	2.2×10^{-8}
-2200	3.3×10^{-9}	1.8×10^{-8}
-2600	2.8×10^{-9}	1.6×10^{-8}

By comparing the figures from Tables VI-6 and VI-7, one should be able to decide about the particular soil liner permeability K_1 required. For this particular case, one can see that the choice will be quite difficult since it may be impractical to compact the soil to yield the low range of permeabilities indicated in Table VI-7.

The inspection of Equation 6 reveals that the required permeability is controlled by the magnitude of y and D_t. The term -105.4 in the left hand side of the equation is not very influential in determining the k_1 value. Not so, when y and D_t are relatively small. In this situation the term $[h_d(q/K_f)^{-1/(2+3\lambda)}]$ becomes quite significant. Table VI-8 presents the values of this term for different ranges of h_d, λ, K_f and q. The ranges chosen are deliberately broad to overemphasize the significance of each of the parameters.

TABLE VI-8. VALUES OF THE TERM $h_d \left[\frac{q}{K_f}\right]^{-1/2+3\lambda}$ FOR DIFFERENT VALUES OF h_d, λ, K_f and q.

q cm sec^{-1}	K_f cm sec^{-1}	h_d = -10 cm		h_d = -300 cm	
		λ = 0.5	λ = 5	λ = 0.5	λ = 5
10^{-6}	10^{-4}	-37	-13	-1118	-393
	10^{-6}	-10	-10	-300	-300
10^{-8}	10^{-4}	-139	-17	-4168	-516
	10^{-6}	-37	-13	-1118	-393

The values for q, i.e. the required limiting flux, and k_f, i.e. the saturated permeability of the underlying soil, should be known to the designer of the soil liner. Consequently, the designer should have no problems in deciding on the row of the table corresponding to the particular system. The choice of a particular column of Table VI-8 is a much more difficult step since it involves information regarding the moisture characteristic curve (MCC) of the underlying soil, h_d and λ. Since the MCC is not routinely determined in geotechnical laboratories we will not recommend that it be determined. On the other hand, some of the combinations between K_f, h_d, and λ are not possible. Thus, a soil with a permeability $K_f = 10^{-4}$ cm sec^{-1}, an air-entry pressure $h_d = -300$ and a $\lambda = 0.5$ probably does not occur in nature and the term in Table VI-8 will almost never be lower than -10^3. As we mentioned in the case in which the depth of the waste fluid, y, and that of the solid waste, D_t, are small, the relative significance of this term becomes important. Table VI-8 indicates that this is true the lower the ratio q/K_f.

Table VI-6 shows that, if the waste fluid plus the solid waste head is large (e.g. larger than 50 feet), the permeability of the undisturbed underlying soil becomes critical in generating a low permissible flux, since for this situation a deep soil liner of low permeability is required, and this situation may not be economical.

For the situation in which the condition of unsaturated flow is not observed, i.e. when $h_f \geq h_d$, the downward movement in the underlying soil will occur as saturated flow. According to McWhorter and Nelson (1979), such a situation will be observed, for instance, for the following set of data:

$y = 10$ feet

$D_t = 3$ feet

$D_l = 1$ foot

$K_t = 10^{-4}$ cm sec^{-1}

$K_l = 10^{-8}$ cm sec^{-1}

$K_f = 10^{-7}$ cm sec^{-1}

$h_d < 0$

Assuming $h_c = -50$ cm, the flux can be calculated using the equation (Equation 22 from McWhorter and Nelson, 1979):

$$q = K_f \frac{(L + y + D_t + D_l - h_c)}{(L + D_t \frac{K_f}{K_t} + D_l \frac{K_f}{K_l})} \tag{7}$$

The calculated flux below the soil liner when the wetting front is at a distance L equal to 10 m below the liner, will be 1.13×10^{-7} cm sec $^{-1}$.

If the soil porosity, n, is equal to 0.4 and the initial volumetric moisture content θ_i equal to 0.25, the relationship between time t and L can be expressed, using:

$$\frac{n-\theta_i}{K_f}\left[L + (D_t \frac{K_f}{K_t} + D_l \frac{K_f}{K_l} - y - D_t - D_l + h_c) \ln \left(\frac{L + y + D_t + D_l - h_c}{y + D_t + D_l - h_c}\right)\right] = t \tag{8}$$

For the set of data considered, the time t corresponding to L = 10 m is equal to 38.3 years. Since the flow was saturated and the volume occupied by the incoming waste effluent accounts for 15% of the soil bulk volume ($n - \theta_i = 0.15$), the length of the waste effluent column saturating the underlying soil is equal to 150 cm. The ratio of 150 cm over 38.3 years results in an average q equal to 1.24×10^{-7} cm sec^{-1}, which checks well with the figure calculated using Equation 7.

The presented numerical example has many limitations and the designer should be aware of them:

a. The real system to be analyzed may have variable dimensions in time, for instance if the incoming waste accumulates in the waste disposal site.

b. Flow properties of all traversed strata can be altered in time.

c. Some of the characteristics of the underlying soil (h_d and λ). which have been discussed in this presentation can be very sensitive to minute soil intrinsic property changes. Thus, an apparently homogeneous underlying soil can have, at different locations along the vertical flow direction, different h_d and λ values.

d. The temporary physico-chemical retention of the potential contaminants present in the original waste fluid has been disregarded in this analysis. Most of the experimental work on miscible displacement performed so far refers to saturated flow. In unsaturated condition, the processes of diffusion, hydrodynamic dispersion, adsorption, phase change of chemical species, etc., are expected to be connected in a more complex manner.

The most important merit of the presented analysis is that it considers the flow to be unsaturated which is a reality in the field, in most instances.

The analysis for design can be carried out using other procedures. If the system is more complicated than the one presented in our example, advantage can be gained by using a computer assisted numerical analysis.

Note: See Chapter 5 for references.

APPENDIX VII

CASE STUDY ANALYSIS METHODOLOGY

This Appendix illustrates the case study method of analysis for developing project costs, and possibly other project components. Depending upon the type and size of project envisioned, the case study method can range from a fairly simple analysis to a very complex procedure. Our example case study is a straightforward and simple illustration of the technique.

Case Study of Community X for a Waste Impoundment

A site within Community X has been chosen as the location of a hazardous waste impoundment facility, which is to serve the surrounding metropolitan area containing several industrial concerns. The site is flat and the facility has the design criteria and parameters shown in Table VII-1.

TABLE VII-1. DESIGN CRITERIA AND PARAMETERS

Item	Criteria value
Flow	
Average design flow	60 gpm (4000 ft^3/day)
Pond	
Minimum requirement	120 acres
Cell size	15 acres
Number of cells	8
Total design area	120 acres
Pond depth	
Freeboard	2 feet
Minimum (for liquid seal)	1 foot
Storage	4 feet
Total design depth	7 feet
Embankments	
Slope	3:1
Top width (minimum)	8 feet
Liners	
Primary	45 mil reinforced CSPE
Secondary	30 mil reinforced CPE
Monitoring wells	10
Life	20 years

The engineer for the facility has determined that thin polymeric membrane liners are necessary to contain the wastes adequately. That decision was effected by the inadequacy of the native soil and the unavailability of a nearby suitable clayey soil for construction into a liner. The wastes to be impounded are not radioactive. The literature has revealed that the wastes to be impounded do not adversely affect the reinforced chlorosulfonated polyethylene liner nor do they adversely affect the chlorinated polyethylene liner. Compatiblity testing accomplished during the design phase had confirmed the above conclusion. The owner and the engineer have decided to use a double liner system with the following configuration. A 30 mil reinforced CPE liner (secondary liner) is placed over a graded compacted native soil. On top of the CPE liner is a three foot layer of moderately compacted native soil which contains the perforated pipe drain system. The perforated pipe trench is backfilled with filter sand or gravel. A thin soil layer is then placed over the three foot layer. A 45 mil reinforced CSPE is placed on top as the primary liner. The monitoring system consists of one well per cell located near the lowest point of the underdrain system plus two groundwater observation wells perforated in the native soil subgrade located down gradient of the impoundment.

Due to possible wave action in the impoundment facility during adverse weather conditions, two feet of freeboard is provided. Impoundment embankments are to be constructed with 3:1 slopes from material obtained near or on the site. To minimize erosion of these earthen embankments or dikes, a vegetative and/or rock cover may be utilized. A minimum top width of eight feet is required. Particulate emissions from impoundment areas will be minimized by maintaining solids in a slurry or liquid state. Total design depth of the pond is the sum of the required freeboard, the minimum storage depth necessary to maintain the contents in a liquid state, and the design storage depth. In order to maintain operation flexibility and maximize efficiency and effectiveness, the impoundment is divided into smaller cells. Each cell has an area of 15 acres. In case of leakage or maintenance operations, liquid wastes can be pumped to adjacent cells. The ability to drain individual cells provides flexibility in control of the liquid depth of a cell thereby increasing operation reliability.

Table VII-2 presents the capital costs for the waste impoundment facility. Table VII-3 shows the operating costs and Table VII-4 presents the total annual costs of the facility.

TABLE VII-2. CAPITAL COSTS FOR WASTE IMPOUNDMENT FACILITY

Component	Cost[a], thousands of dollars
Construction	
Excavation	630
Smoothing and clearing	114
Drainage and collection	165
Liner[b]	10,694
Monitoring system[c]	120
Subtotal	11,723
Impoundment closure	
Final cover	30
Revegetation	120
Monitoring	48
Subtotal	198
Construction contingencies	
Engineering, administrative, legal and permit costs (25%)	2,980
Total Impoundment Capital Cost	14,901

[a] Based on prices quotes from August, 1980.

[b] Primary liner and secondary liner plus installation. Based on $0.85/sq.ft. reinforced chlorosulfonated polyethylene and 0.70/sq. ft. CPE.

[c] Assume 10 wells.

TABLE VII-3. OPERATING COSTS FOR IMPOUNDMENT FACILITY

Item	Annual cost $/yr	Unit cost $/1,000 gal
Impoundment		
Power	24,880	0.024
Operation and maintenance	116,120	0.11
Total	141,000	0.13

TABLE VII-4 ANNUAL COSTS FOR IMPOUNDMENT FACILITY

Component	Annual costs
Capital costs[a]	$1,995,000
Operating costs	141,000
Total	$2,136,000

[a] Twenty year amoritization at 12 percent interest - capital recovery factor = 0.13388.

APPENDIX VIII

SUGGESTED STANDARDS FOR REPRESENTATIVE FLEXIBLE POLYMERIC MEMBRANES AVAILABLE IN OCTOBER 1982

In view of the lack of accepted standards to cover currently available flexible membrane materials for lining waste disposal impoundments, suggested standards for representative membranes currently available (October 1982) are presented in this appendix. The values are preliminary and subject to change. They are based largely upon the properties and tests discussed in Table 3-7 in Chapter 3 and reflect some of the current efforts to develop standards.

These tables of values should not be used to select materials. Selection, as indicated in Chapter 8, should be based upon factors of compatibility, durability, etc. They are intended to be used as a means of assuring the quality of the lining material that is installed in the waste disposal facility and of assuring that the quality of the material is the same as was observed in the compatibility tests.

The standards present values for different properties which can characterize the membranes currently on the market. By themselves, these standards are not adequate to predict product performance, nor can they be used for engineering design purposes. For example, the low temperature resistance numbers represent qualities measured after a few minutes exposure at a given temperature and should not be interpreted or extrapolated into installation temperature qualities or comparisons. Correlations of specific properties and tests with field performance of lining materials have not been established, but the results of the tests indicate the quality of the specific material under test.

VIII.1 GENERAL REQUIREMENTS FOR MANUFACTURE OF FLEXIBLE POLYMERIC MEMBRANES

Membranes shall be first quality designed and manufactured for the purpose of lining waste disposal impoundments. They shall be manufactured of virgin polymers and specifically compounded of high quality ingredients to produce flexible, durable, watertight membranes. Compounding ingredients shall either be soluble in the polymer or, if solid, shall pass through a No. 325 sieve, i.e. have particle size of 44 µm or less. All ingredients should be well dispersed through the compound prior to being formed into membranes. No water soluble ingredients can be used in the compound; neither can the ingredients contain water-soluble components.

The resultant membranes shall be free from dirt, oil, foreign matter, scratches, cracks, creases, bubbles, pits, tears, holes, pinholes, or other defects that may affect serviceability and shall be uniform in color, thickness, and surface texture. The sheeting shall be capable of being seamed both in the factory and in the field to yield seams that are as resistant to waste liquids as the sheeting.

Note: Recycling of clean scrap compound is allowed up to 5% by weight of the compound. The recycling of scrap containing fiber is generally not considered to be good practice; however, the effects of such recycling have not been established at this time and tests are underway to resolve this question.

VIII.2 SUGGESTED TEST METHODS AND REQUIRED PROPERTIES FOR REPRESENTATIVE LINERS

Suggested methods for testing flexible polymeric membranes for acceptance and quality control and required values for properties of representative liner materials are presented in the following seven tables:

VIII-1. Suggested Test Methods for Testing of Flexible Polymeric Membrane Liners.

VIII-2.. Titles of ASTM Test Methods Used in Membrane Liner Specifications.

VIII-3. Suggested Standards for Flexible Membrane Liners Without Fabric Reinforcement - Crosslinked Membranes.

VIII-4. Suggested Standards for Flexible Membrane Liners Without Fabric Reinforcement - Thermoplastic Membranes.

VIII-5. Suggested Standards for Flexible Membrane Liners Without Fabric Reinforcement - Partially Crystalline Membranes.

VIII-6. Suggested Standards for Fabric-Reinforced Flexible Membrane Liners - Thermoplastic Coatings of CPE, Nitrile Rubber - PVC, EPDM, and EIA.

VIII-7. Suggested Standards for Fabric-Reinforced Flexible Membrane Liners - Thermoplastic Chlorosulfonated Polyethylene (CPSE).

For quality control purposes, it is suggested that random samples be taken from each 10,000 square yards of sheeting; however, a minimum of five samples for quality control testing should be taken from each job. Each sample should be three by six feet and should include a factory seam if the membrane requires factory fabrication. The minimum tests that should be performed for quality control purposes are those that are listed under mechanical properties.

Table VIII-1 presents all of the suggested test methods arranged by type of membrane and by analytical properties, mechanical properties, and tests of the effects of environmental and aging conditions on properties. The types of polymeric membranes are:

1. Crosslinked membranes without fabric reinforcement.
2. Thermoplastic membranes without fabric reinforcement.
3. Crystalline membranes without fabric reinforcement.
4. Fabric-reinforced membranes which include both membranes with crosslinked coatings and those with thermoplastic coatings.

Note: No fabric-reinforced membranes with crystalline coatings are currently available in thicknesses of 20 mils or greater.

Table VIII-2 lists all of the ASTM tests that are suggested, showing their titles and whether they are specifications. One of the test methods (ASTM D1239) was recently discontinued; however, it can be used as a test for the resistance of plastic sheetings to extraction.

Table VIII-3 presents the suggested standards for membrane liners without fabric reinforcement that are based upon crosslinked compounds. Membranes of the following polymer types are included in this table: butyl rubber, crosslinked chlorinated polyethylene, epichlorohydrin rubbers, ethylene propylene rubbers, and neoprene. The values listed are for sheetings of 45 mils nominal thickness, which is the intermediate thickness for commercially available membranes of this type. For most of the polymers, membranes are also available in nominal thicknesses of 30 and 60 mils. Breaking factor, modulus, tear resistance, and factory seam strength (in shear), are essentially proportional to the thickness and their required values for specification can be estimated. To calculate those properties which are affected by thickness the following formula can be used.

$$\text{Required value for thickness other than 45 mils} = \frac{\text{other thickness in mils}}{\text{45 mils}} \times \text{Value of property of 45 mil sheeting}$$

For example, breaking factor (strength) of 30 mil butyl rubber sheeting equals 30/45 times 54.0 lb or 36.0 pounds force. Values for other properties, such as specific gravity, elongation at break, low temperature brittleness, dimensional stability, resistance to soil burial, water absorption, ozone resistance, and effects of air oven aging are essentially independent of thickness with respect to required values.

Table VIII-4 presents the suggested standards for thermoplastic flexible membrane liners without fabric reinforcement. The thermoplastic sheetings that are included in the table are chlorinated polyethylene, polyvinyl chloride, and oil-resistant polyvinyl chloride.

Table VIII-5 covers the suggested standards for partially crystalline membranes which are elasticized polyolefin, high-density polyethylene, and high-density polyethylene alloy. Only one thickness of elasticized polyolefin, i.e. 20 mils, is currently available; however, in the case of the high-density polyethylene, thicknesses from 20 to 120 mils are available as well as thicknesses of 20 to 60 mils for HDPE-alloy. For sheetings of the latter two polymers, required values for properties such as tensile at yield, tensile strength, tear resistance, and seam strength vary proportionately with the thickness. Other properties such as specific gravity, volatile loss, elongation at yield, elongation at break, modulus of elasticity, dimensional stability, low temperature brittleness, resistance to soil burial, ozone resistance, resistance to environmental stress cracking, and water extraction can be considered for these specifications to be independent of the thickness of the sheeting.

Tables VIII-6 and VIII-7 present the suggested standards for representative fabric-reinforced flexible polymeric membrane liners. Strength values for these membranes depend upon the fabric reinforcement used. Fabric reinforcement increases tensile strength, puncture resistance and tear resistance, and reduces shrinkage and elongation at break. Table VIII-6 covers those membranes coated with thermoplastic chlorinated polyethylene, nitrile - polyvinyl chloride, EPDM, and ethylene interpolymer alloy. Table VIII-7 covers fabric-reinforced chlorosulfonated polyethylene lining materials. It covers both standard (potable grade) CSPE coated membranes and the industrial grade of CSPE coating which has a lower water absorption than the standard grade. Minimum required values for potable and industrial grade CSPE membranes are equal except for breaking strength, strength of factory seams, and water absorption.

No required values are suggested for seam strength tested in the peel mode nor by dead weight test because of the lack of data. These are, however, considered to be important tests for assessing adhesion in seams made both in the factory and in the field. Peel and dead weight tests are particularly useful in assessing the durability of seams. ASTM Test Methods D413, "Adhesion to Flexible Substrate (Machine Method)" and D1876, "Peel Resistance of Adhesives (T-Peel Test)" appear to be the appropriate test methods for assessing peel strength of liner seams. Also, the effect of soil burial on the peel strength appears to be needed. Studies are under way to develop this information and it is anticipated the required values for these properties will be included in the next edition of this Technical Resource Document.

TABLE VIII-1 SUGGESTED ASTM METHODS FOR TESTING OF FLEXIBLE POLYMERIC MEMBRANE LINERS

Properties	Membranes without fabric reinforcement[a]			Fabric-Reinforced membranes[b]
	XL	TP	CX	
Analytical properties				...
Specific gravity	D297, Mtd A	D792, Mtd A	D792, Mtd A	D1203, Mtd A (30 mil sheet)
Volatile loss	...	D1203, Mtd A	D1203, Mtd A	
Mechanical properties				
Thickness				
1. Overall	D1593, ¶8.1.3	D1593, ¶8.1.3	D1593, ¶8.1.3	D751
2. Coating over scrim	na	na	na	Optically
Minimum tensile properties (in both machine and transverse directions)	D412	D882	D638	D751, Mtd A (grab)
1. Breaking strength of fabric	na	na	na	D751, Mtd A (grab)
2. Breaking elongation of fabric	na	na	na	D751, Mtd A (grab)
3. Tensile at yield	na	na	D638	na
4. Elongation at yield	na	na	D638	na
5. Breaking factor	D412	D882, Mtd A,B	D638	D751, Mtd A
6. Elongation at break	D412	D882, Mtd A,B	D638	D751, Mtd A
7. Stress at 100% elongation	D412	D882, Mtd A,B	D638	na
Modulus of elasticity	na	na	D638	na
Tear strength	D624, Die C	D1004, Die C	D1004, Die C	D751, Mtd B (tongue) (8" x 8" specimen)
Hardness, Duro A or D (5 second readings)	D2240	D2240	D2240	D2240[c]
Hydrostatic resistance	...	D751, Mtd A	...	D751, Mtd A, Proc 1
Ply adhesion	na	na	na	D413, Mtd A
Strength of factory seam (test in shear mode)	D3083/ D882, Mtd A at 2 in/min	D3083/ D882, Mtd A at 2 in/min	D3083/ D882, Mtd A at 2 in/min	D751 (mod)[d] at 12 in/min
Environmental and aging effects				
Dimensional stability	D1204 (7 d @ 100°C)	D1204 (15 min @ 100°C)	D1204 (15 min @ 100°C)	D1204 (1 h @ 100°C)
Low temperature brittleness	D746, Proc B[e]	D1790[e]	D746, Proc B[e]	D2136[f]
Resistance to soil burial for 120 d[g]	D3083, Sec. 9.5	D3083, Sec. 9.5	D3083, Sec. 9.5	D3083, Sec. 9.5
Tensile at yield	na	na	D638	na
Tensile at fabric break	na	na	na	D751
Tensile at break	D412	D882	D638	D751
Elongation at break	D412	D882	D638	D751
Modulus of elasticity	na	na	D638	na
Air oven aging (conditions vary with polymer)	D573	...	D573	D573
Breaking factor	D412	...	D638	...
Elongation at break	D412	...	D638	...
Stress at 100% elongation	D412	...	...	...
Hardness	D2240	...	...	...
Tear resistance	...	...	...	D751, Mtd B (tongue) (8" x 8" specimen)
Ozone resistance at 40°C	D1149 50-100 pphm O_3 20-50% extension 50 h - 7 d	D1149 100 pphm O_3 70% extension 7 d	D1149/D518 100 pphm O_3 Bent loop 7 d	D1149/D518 100 pphm O_3 Bent loop 7 d
Environmental stress cracking	na	na	D1693	na
Water absorption	D471 7 d @ 70°C	...	...	D471 14 d @ 21°C 14 d @ 70°C
Water extraction	D3083/D1239	D3083/D1239	D3083/D1239	D3083, ¶9.6

[a] XL = Crosslinked (vulcanized) rubbers; TP = thermoplastic polymers; CX = crystalline polymers; na = not applicable.
[b] Includes both TP and XL coatings.
[c] On selvage edge.
[d] Run 12 inches per minute.
[e] Determination of the temperature at which membranes exhibit brittle failure under specified impact conditions.
[f] Bend specimen over 1/8 in. mandrel after four hours at the test temperature.
[g] Buried specimen 1" x 6".

TABLE VIII-2. TITLES OF ASTM TEST METHODS USED IN MEMBRANE LINER SPECIFICATIONS[a]

ASTM Number	Title and pertinent sections
D297-81	Rubber Products - Chemical Analysis. Section 15-Density; Section 34-Referee Ash Method.
D412-80	Rubber Properties in Tension.
D413-76	Rubber Property - Adhesion to Flexible Substrate.
D471-79	Rubber Property - Effect of Liquids.
D518-61 (1974)	Rubber Deterioration - Surface Cracking.
D573-81	Rubber - Deterioration in Air Oven.
D624-73	Rubber Property - Tear Resistance.
D638-80	Tensile Properties of Plastics.
D746-79	Brittleness Temperature of Plastics and Elastomers by Impact.
D751-79	Coated Fabrics.
D792-66 (1979)	Specific Gravity and Density of Plastics by Displacement.
D882-81	Tensile Properties of Thin Plastic Sheeting.
D1004-66 (1981)	Initial Tear Resistance of Plastic Film and Sheeting.
D1149-81	Rubber Deterioration - Surface Ozone Cracking in a Chamber (Flat Specimens).
D1203-67 (1974)	Loss of Plasticizer from Plastics (Activated Carbon Methods).
D1204-78	Linear Dimensional Changes of Nonrigid Thermoplastic Sheeting or Film at Elevated Temperature.
D1239-55	Resistance of Plastic Films to Extraction by Chemicals (test method discontinued in 1980).
D1593-80	Nonrigid Vinyl Chloride Plastic Sheeting, Specification for.
D1693-70 (1980)	Environmental Stress-Cracking of Ethylene Plastics.
D1790-62 (1976)	Brittleness Temperature of Plastic Film by Impact.
D2136-66 (1978)	Coated Fabrics - Low-Temperature Bend Test.
D2240-81	Rubber Property - Durometer Hardness.
D3083-76 (1980)	Flexible Poly(Vinyl Chloride) Plastic Sheeting for Pond, Canal, and Reservoir Lining, Specification for. Section 9.5 Soil Burial; Section 9.6 Water Extraction; Section 9.4 Pinholes and Cracks.

[a] As listed in the 1981 and 1982 issues of the ASTM standards. Number in parentheses indicates the year of last reapproval by the committee with jurisdiction for the standard.

TABLE VIII-3. SUGGESTED STANDARDS FOR FLEXIBLE MEMBRANE LINERS WITHOUT FABRIC REINFORCEMENT

Crosslinked Polymeric Membranes of 45 Mils Nominal Thickness

Properties	ASTM test method[a]	Butyl rubber	CPE - Crosslinked	ECO/CO[b]	EPDM	Neoprene
Analytical properties						
Specific gravity	D297-A	1.20±0.05	1.38±0.05	1.49±0.06	1.18±0.03	1.48±0.05
Mechanical properties						
Thickness, % tolerance	D1593	+15 -10	±5	+15 -10	+15 -10	+15 -10
Minimum tensile properties (each direction):	D412					
(1) Breaking factor, ppi width		54.0	54.0	54.0	63.0	67.5
(2) Elongation at break, %		300	300	200	300	250
(3) Stress at 100% elongation, ppi width		(c)	(c)	(c)	(c)	(c)
Tear strength, lb (min)	D624	6	5	6	6	6
Hardness Duro A, pts	D2240	60±10	68±8	70±8	60±10	60±10
Strength of factory seams (tested in shear), ppi width (min)	D3083/ D882	43.2	44.0	43.2	50.4	54.0
Environmental and aging effects on properties						
Dimensional stability (each direction), percent change (max)	D1204	2	2	2	2	2
Low temperature (brittleness temperature), °F (max)	D746	-40	-40	CO 0 ECO -20	-75	-30
Resistance to soil burial for 120 days (maximum percent change from original value):	D3083					
(1) Breaking factor		10	10	10	10	10
(2) Elongation at break		20	10	25	20	20
(3) Stress at 100% elongation		(c)	(c)	(c)	(c)	(c)
(4) Modulus of elasticity		na	na	na	na	na
Heat aging:	D573					
Conditions:		7 d @ 116°C	7 d @ 121°C	7 d @ 116°C	7 d @ 116°C	70 h @ 100°C
(1) Breaking factor, ppi, width (min)		37.8	48.0	45.0	54.0	57.4
(2) Elongation, % (min)		210	200	125	210	50
(3) Hardness change, Duro A points, (max)		(c)	8	(c)	(c)	(c)
Ozone resistance at 40°C Other conditions	D1149	50 pphm O_3 20% extension 100 h No cracks[d]	100 pphm O_3 20% extension 7 d No cracks[d]	100 pphm O_3 20% extension 7 d No cracks[d]	100 pphm O_3 50% extension 7 d No cracks[d]	50 pphm O_3 20% extension 100 h No cracks[d]
Water absorption, % (max)	D471	2	10	10	2	12
Water extraction, % (max)	D3083	(c)	(c)	(c)	(c)	(c)

[a] For more details regarding conditions and titles of test methods, see Tables VIII-1 and VIII-2.

[b] Epichlorohydrin rubbers. ECO = copolymer; CO = Homopolymer.

[c] Data unavailable at this time.

[d] No cracks visible under 7x magnification.

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TABLE VIII-4. SUGGESTED STANDARDS FOR FLEXIBLE MEMBRANE LINERS WITHOUT FABRIC REINFORCEMENT

Thermoplastic Membranes

Properties	ASTM test method[a]	CPE		PVC			PVC-OR[b]
Analytical properties							
Specific gravity	D792-A	1.20 min	1.20 min	1.20 min	1.20 min	1.20 min	1.20 min
Volatile loss, % (max)	D1203-A	0.5	0.5	0.7	0.7	0.7	0.5
Mechanical properties							
Thickness,	D1593						
(1) Nominal, mils		20	30	20	30	45	30
(2) Actual, mils (min)		19	28.5	19	28.5	42.75	28.5
Minimum tensile properties in each direction	D882						
(1) Breaking factor, ppi width		34	43	46	69	104	69
(2) Elongation at break, %		250	300	300	300	300	300
(3) Stress at 100% elongation, ppi width		8	12	18	27	40.5	27
Tear strength, lb (min)	D1004	3.5	4.5	5.3	8	12.0	8
Strength of factory seams, (tested in shear) ppi width (min)	D882	27	34	36.8	55.2	82.8	55.2
Hydrostatic resistance, psi (min)	D751-A	75	100	60	82	100	82
Environmental and aging effects on properties							
Dimensional stability, % change (max)	D1204	16	16	5	5	5	5
Low temperature (brittleness temperature), °F (max)	D1790	-20	-20	-15	-20	-20	0
Resistance to soil burial for 120 days (maximum percent change from original value)	D3083						
(1) Breaking factor		-5	-5	-5	-5	-5	-5
(2) Elongation at break		-20	-20	-20	-20	-20	-20
(3) Stress at 100% elongation		±20	±20	±10	±10	±10	±10
Ozone resistance at 40°C	D1149	(c)	(c)	(c)	(c)	(c)	(c)
Water extraction, % (max)	D3083/ D1239	-0.35	-0.35	-0.35	-0.35	-0.35	-0.35

[a] For more details regarding conditions and titles of test methods, see Tables VIII-1 and VIII-2.

[b] Poly(vinyl chloride) - oil resistant.

[c] Data unavailable at this time.

TABLE VIII-5
SUGGESTED STANDARDS FOR FLEXIBLE MEMBRANE LINERS WITHOUT FABRIC REINFORCEMENT
Partially Crystalline Membranes

Properties	ASTM test method[b]	ELPO[a] 20 mil	HDPE 80 mil	HDPE-Alloy 40 mil
Analytical properties				
Specific gravity	D792-A	0.92±0.05	0.930 min	0.930 min
Volatile loss, % max	D1203-A	0.5	(c)	0.1
Mechanical properties				
Thickness, mils (range)	D1593	17-24	72-80	36-40
Tensile properties, minimum in each direction	D638			
(1) Tensile at yield, ppi width		(c)	120	60
(2) Elongation at yield, %		(c)	10	20
(3) Breaking factor, ppi width		34	120	140
(4) Elongation at break, %		500	500	600
(5) Stress at 100% elongation, ppi width		12.8	(c)	(c)
Modulus of elasticity, psi (min)	D638	(c)	80,000	45,000
Tear strength, lb (min)	D1004	5.1	40	20
Shore D hardness, pts	D2240	(c)	(c)	(c)
Bonded seam strength, factory seam, breaking factor, ppi width	D3083	27.2	108	80
Environmental and aging effects on properties				
Dimensional stability[d], % change (max)	D1204	4	3	2
Low temperature (brittleness temperature), °F (max)	D746	-76	-40	-40
Resistance to soil burial for 120 days (maximum percent change from original value)	D3083			
(1) Tensile at yield		(c)	10	10
(2) Elongation at yield		(c)	10	10
(3) Tensile at break		10	10	10
(4) Elongation at break		10	10	10
(5) Stress at 100% elongation		10	(c)	(c)
(6) Modulus of elasticity		(c)	10	10
Air oven aging	D573[e]			
(1) Breaking factor, ppi, width, (min)		33	(c)	(c)
(2) Elongation, % (min)		425	(c)	(c)
Ozone resistance at 40°C	D1149/D518	No cracks[f]	(c)	No cracks[f]
Environmental stress cracking, h, (min)	D1693	(c)	500	500
Water extraction, % (max)	D1239	-0.35	(c)	(c)

[a] Elasticized polyolefin.

[b] For more details regarding conditions and titles of test methods, see Tables VIII-1 and VIII-2.

[c] Data unavailable at this time.

[d] Maximum percent change in each direction in 15 min at 100°C.

[e] 14 days at 70°C.

[f] No cracks visible at 7x magnification.

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TABLE VIII-6. SUGGESTED STANDARDS FOR FABRIC-REINFORCED FLEXIBLE MEMBRANE LINERS
Thermoplastic Coatings of CPE, Nitrile Rubber - PVC, EDPM, and EIA

Properties	ASTM test method[a]	CPE			CPE alloy (CPE-A)	Nitrile rubber PVC	EPDM TP	Ethylene inter-polymer alloy (EIA)
Analytical properties								
Volatile loss, % (max)	D1203	0.5	0.5	0.5	0.7	1.0	0.5	1.0
Mechanical properties								
Thickness	D751							
(1) Nominal, mils	Optically	36	36	45	36	30	30	30
(2) Minimum, mils		32	34	41	34	27	27	27
(3) Coating over fabric, mils (min)		11	11	11	11	11	11	7
Minimum tensile properties (each direction)	D751-A (grab)							
(1) Breaking strength, lb		120	200	200	200	50[b]	100	400
(2) Breaking factor of sheet without fabric reinforcement, lb		(c)	(c)	(c)	(c)	(c)	(c)	(c)
(3) Elongation at break of sheet without fabric reinforcement, lb		(c)	(c)	(c)	(c)	(c)	(c)	(c)
(4) Stress at 100% elongation of sheet without fabric reinforcement		(c)	(c)	(c)	(c)	(c)	(c)	(c)
Tear resistance, lb (min)	D751-B	25	35	75	60	20	25	125
Hydrostatic resistance, psi (min)	D751-A-Proc 1	160	250	300	250	160	160	500
Ply adhesion (each direction), lb/in width (min)	D413-A	10	6	8	7	8	8	10
Strength of factory seam, lb (min)	D751-Mod[d]	96	160	160	160	80	80	320
Environmental and aging effects on properties								
Dimensional stability (each direction), % change (max)	D1204	2	2	2	2	2	2	2
Low temperature (brittleness temperature), °F (max)	D2136	-40	-40	-40	-40	-20	-20	-30
Air oven aging for 30 d at 100°C	D573							
Tear resistance after aging, lb (min)	D751-B	20	25	25	25	15	20	90
Resistance to soil burial for 120 days (maximum percent change from original value)	D3083							
(1) Breaking strength of fabric		-25	-25	-25	-25	-25	-25	-25
(2) Breaking factor of sheet without fabric reinforcement		-5	-5	-5	-5	-20	-10	-10
(3) Elongation at break of sheet without fabric reinforcement		-20	-20	-20	-20	-20	-20	-20
(4) Stress at 100% elongation of sheet without fabric reinforcement		+10	+10	+25	+25	+30	+30	+15
Ozone resistance at 40°C (bent loop at 100 pphm O_3 for 7 days)	D1149 D518	(c)	(c)	(c)	(c)	no cracks[e]	no cracks[e]	no cracks[e]
Water extraction, % (max)	D3083	(c)	(c)	(c)	(c)	(c)	(c)	0.35
Water absorption, % gain (max)	D471							
14 days at 21°C		(c)	(c)	(c)	(c)	(c)	(c)	1
14 days at 70°C		(c)	(c)	(c)	(c)	(c)	(c)	2

[a] For more details regarding conditions and titles of test method, see Tables VIII-1 and VIII-2.

[b] Fabric break. Coating is stronger than the fabric and has a breaking strength of 80 lb and 120% minimum elongation at break.

[c] Data unavailable at this time.

[d] Measured at 12 inches per minute, specimen 4" wide and with 4 1/2" on either side of seam.

[e] No visible cracks at 7x magnification.

TABLE VIII-7. SUGGESTED STANDARDS FOR FABRIC-REINFORCED FLEXIBLE MEMBRANE LINERS

Thermoplastic Chlorosulfonated Polyethylene (CSPE)
Potable and Industrial Grades[a]

Properties	ASTM test method[b]	CSPE liner type[a]				
		A	B	C	B	C
Analytical properties						
Volatile loss, % (max)	D1203	0.5	0.5	0.5	0.5	0.5
Mechanical properties						
Thickness						
(1) Nominal		30	36	36	45	45
(2) Actual, mils (min)	D751	27	27	34	41	41
(3) Coating over scrim, mils (min)	Optically	11	11	11	11	11
Minimum tensile properties (each direction)	D751-A(Grab)					
(1) Breaking strength of fabric, lbf		60[c]	120	200	125	200 250[d]
(2) Breaking factor of sheet without fabric reinforcement, lbf		(e)	(e)	(e)	(e)	(e)
(3) Elongation at break of sheet without fabric reinforcement, %		(e)	(e)	(e)	(e)	(e)
(4) Stress at 100% elongation of sheet without fabric reinforcement, lbf		(e)	(e)	(e)	(e)	(e)
Tear resistance, lbf (min)	D751-B	10	25	60	30	70
Hydrostatic resistance, psi (min)	D751-A-Proc 1	80	160	250	180	250
Ply adhesion (each direction), lbf/in width (min)	D413-A	10	10	10	10	10
Strength of factory seam, lbf (min)	D751-Mod[f]	80	96	160 200[d]	96 100[d]	180 250[d]
Environmental and aging effects on properties						
Dimensional stability (each direction), % change (max)	D1204	7.5	2	2	3	2
Low temperature (brittleness temperature), °C (max)	D2136	-40	-40	-40	-40	-40
Air oven aging for 30 days at 100°C	D573					
Tear resistance after aging, lbf (min)	D751-B	5	20	25	25	25
Resistance to soil burial for 120 days (maximum percent change from original value)	D3083					
(1) Breaking strength of fabric		-25	-25	-25	-25	-25
(2) Breaking factor of sheet without fabric reinforcement		-5	-5	-5	-5	-5
(3) Elongation at break of sheet without fabric reinforcement		-20	-20	-20	-20	-20
(4) Stress at 100% elongation of sheet without fabric reinforcement		+10	+10	+30	+10	+30
Water extraction, % (max)	D3083	(e)	(e)	(e)	(e)	(e)
Water absorption, % gain (max)	D471					
14 days at 21°C		1.5[d]	1.5[d]	1.5[d]	1.5[d]	1.5[d]
14 days at 70°C		30[d]	30[d]	30[d]	30[d]	30[d]

[a] Values apply to both grades, except for those specifically noted for industrial grades only. The different types of membranes are classified by the type of fabric that is used to reinforce the membrane. A Type-A membrane is typically reinforced with a 6 x 6 ends per inch (epi) fabric; a Type-B membrane is typically reinforced with an 8 x 8 epi; and a Type-C membrane is typically reinforced with a 10 x 10 epi fabric. Polyester fabric is used for reinforcement.

[b] For more details regarding conditions and titles of test method, see Tables VIII-1 and VIII-2.

[c] Coating is stronger than the fabric and has a breaking strength of 100 lb for 30 mils and 150% minimum elongation at break.

[d] Apply to industrial grades of CSPE membranes only.

[e] No data available at this time.

[f] Measured at 12 inches per minute, specimen 4 1/2" on each side of seam and 4" wide.

GLOSSARY OF TERMS RELATING TO LINER TECHNOLOGY

The intent of this glossary is to define the terms used in this Technical Resource Document. A glossary is considered desirable because of the diverse origins of the liner technology and the broad spectrum of potential users of this document. If possible, generally accepted definitions were selected. The sources of each are indicated with the definition. However, if an appropriate definition could not be found, one was prepared. The definitions are presented by area of expertise, thus some definitions may appear more than once. The areas of expertise are:

1. Admix liner materials
2. Asphalt technology
3. Chemistry
4. Hazardous waste management
5. Hydrology
6. Polymeric membrane liners
7. Site construction
8. Soil science and engineering
9. Solid waste management

After the review period, we propose to combine the final revised list of terms into a single list and to eliminate the references to the sources of the definitions which are presented in the attached list.

GLOSSARY

ADMIX LINER MATERIALS

ADMIX - Two or more materials mixed together at or near the waste disposal facililty to be lined. These materials include asphalt concrete, portland cement concrete, and mixtures of soil and asphalt or portland cement.

ADMIXTURES - Substances that are added to mortar, stucco, cement plaster, and concrete to produce specific results. They may or may not cause a chemical reaction within the above substances, but usualy a chemical reaction does occur. Asphalts may be added for waterproofing compounds (Hornbostel, 1978).

BENTONITE - See Soil Science and Engineering.

COMPACTION - A process of densifying soil cement, soil asphalt, and asphalt concrete by the use of sheepsfoot rollers, rubber-tired rollers, and smooth steel rollers.

HYDRAULIC ASPHALT CONCRETE - See Asphalt Technology Glossary.

SOIL ASPHALT - A compacted mixture of soil and asphalt cement. Cutback or emulsified asphalts are usually avoided.

SOIL CEMENT - A mixture of soil, portland cement, and water. As the cement hydrates, the mixture forms a hard, durable, low strength concrete (Day, 1970).

GLOSSARY

ASPHALT TECHNOLOGY

AGGREGATE - A granular material of mineral composition such as sand, gravel, shell, slag, or crushed stone, used with a cementing medium to form mortars or concrete, or alone as in roadway base courses, railroad ballast, etc. (ASTM, D8).

ASPHALT - A dark brown to black semisolid cementitious material consisting principally of bitumens which gradually liquefy when heated and which occur in nature as such or are obtained as residue in the refining of petroleum (Woods, 1960).

ASPHALT CEMENT - A fluxed or unfluxed asphalt specially prepared as to quality and consistency for direct use in the manufacture of bituminous pavements and having a penetration at 25°C (77°F) of between 5 and 300, under a load of 100g applied for five seconds (ASTM, D8).

ASPHALT MEMBRANE - A relatively thin layer of asphalt formed by spraying a high viscosity, high softening point asphalt cement in two or more applications over the surface to be covered. It is normally 1/4" thick and buried to protect it from weathering and mechanical damage.

ASPHALT PANEL - A laminate consisting of a core of blended asphalt, mineral fillers, and reinforcing fibers sandwiched between protective sheets and a protective coating of hot-applied asphalt.

ASPHALT RUBBER - Asphalt containing a minor amount of ground vulcanized rubbers which can be sprayed on prepared surfaces to form a membrane.

BATTEN - In asphalt technology, a strip usually made of asphalt used to seal the joints between asphalt panels.

BITUMEN - A class of black or dark colored (solid, semisolid, or viscous) cementitious substances, natural or manufactured, composed pricipally of relatively high molecular weight hydrocarbons. Asphalts, tars, pitches, and asphaltites are typical examples of bitumen (ASTM, D8).

BLOWN ASPHALT (AIR-BLOWN ASPHALT) - Asphalt produced in part by blowing air through it at a high temperature. If a catalyst, e.g. ferric chloride or phosphorus pentoxide, is used in the air blowing operation, the product is known as catalytically-blown asphalt (Woods, 1960).

COAL TAR - Tar produced by the destructive distillation of bituminous coal (ASTM, D8).

COURSE - See "Lift".

CUTBACK ASPHALT - Asphalt cement that has been liquefied by blending with petroleum solvents which are also, in this context, called diluents. Upon exposure to atmospheric conditions the diluents evaporate leaving the asphalt cement to perform its function (Asphalt Institute, MS-5).

EMULSIFIED ASPHALT - A mixture of asphalt and water in which the asphalt is held in suspension in the water by an emulsifying agent. Emulsified asphalts may be either cationic or anionic depending on the emulsifying agent used.

HYDRAULIC ASPHALT CONCRETE - Similar to asphalt concrete designed for roadway paving, except that it has a higher mineral filler and asphalt content in order to insure an essentially voidless mix after compaction (Asphalt Institute, MS-12).

LIFT - An applied and/or compacted layer of soil, asphalt, or waste. In a sanitary landfill, a lift is a compacted layer of solid wastes and a top layer of cover material. Also referred to as a course (EPA, 1972).

MASTIC - A mixture of mineral aggregate, mineral filler, and asphalt in such proportions that the mix can be applied hot by pouring or by mechanical manipulation; it forms a voidless mass without being compacted (Asphalt Institute, MS-12).

MINERAL FILLER - A finely divided mineral product of which at least 65% will pass a No. 200 sieve which has a sieve opening of 74 μm. Pulverized limestone is the most common manufactured filler, although other stone dust, silica, hydrated lime, portland cement, and certain natural deposits of finely divided matter are also used (Asphalt Institute, MS-5).

MIX - The amounts of aggregates and asphalt which are combined to give the desired properties in the finished product.

PENETRATION - The consistency of a bituminous material expressed as the distance in tenths of a millimeter (0.1 mm) that a standard needle penetrates vertically into a sample of the material under specified conditions of loading, time, and temperature determined by ASTM D5 (ASTM, D8).

PENETRATION GRADE - Classification of asphalt cement into ranges of penetration values specified in ASTM D946.

SOFTENING POINT - Temperature at which a bitumen softens in the ring-and ball method described in ASTM D2398. Used in the classification of bitumen, particularly of bitumen intending for roofing, because it is indicative of the tendency of a material to flow at elevated temperatures encountered in service.

VISCOSITY GRADE - Viscosity classification for asphalt cement into ranges specified in ASTM D3381.

GLOSSARY

CHEMISTRY

ABSORPTION - Ability of a porous solid material to hold within its body relatively large quantities of gases or liquids (Bennett, 1947).

ACIDITY - Quantitative capacity of aqueous solutions to react with hydroxyl ions. It is measured by titration with a standard solution of a base to a specified end point. Usually expressed as milligrams of calcium carbonate per litre (EPA, 1977).

ADSORPTION - The adhesion of an extremely thin layer of molecules (of gases or liquids) to the surface of solids or liquids with which they are in contact (EPA, 1977).

ALKALINITY - The capacity of water to neutralize acids, a property imparted by the water's content of carbonates, bicarbonates, hydroxides, and occasionally borates, silicates, and phosphates. It is expressed in milligrams of calcium carbonate equivalent per litre (EPA, 1977).

ANALYSIS - The determination of the nature or proportion of one or more constituents of a substance, whether separated out or not (Webster's New World Dictionary).

ASH (FIXED SOLIDS) - The incombustible material that remains after a fuel or solid waste has been burned.

ATTENUATION - Any decrease in the maximum concentration or total quantity of an applied chemical or biological constituent in a fixed time or distance travelled resulting from physical, chemical, and/or biological reaction or transformation (Fed. Regist., 1978).

BOD_5 (Five Day Biochemical Oxygen Demand) - A measure of the relative oxygen requirements of waste-waters, effluents and polluted waters. BOD values cannot be compared unless the results have been obtained under identical test conditions. The test is of limited value in measuring the actual oxygen demand of surface waters (APHA - AWWA - WPCF, 1975).

COD (Chemical Oxygen Demand) - A measure of the oxygen equivalent of that portion of the organic matter in a sample that is susceptible to oxidation by a strong chemical oxidant (APHA - AWWA - WPCF, 1975).

CONTAMINATION - A substance or substances that renders a body of water, soil, sample, etc. impure, unclean or corrupt by contact (Webster's New World Dictionary).

DIFFUSION - The material permeation of two or more substances due to the kinetic activity of their molecules, so that a uniform mixture or solution results. Diffusion occurs with all forms of matter; it is most rapid for gases, somewhat slower for liquids and for solids in solution.

EXTRACTABLES - Components or substances removable from a solid or liquid mixture by means of an appropriate solvent (Hampel and Hawley, 1976).

HYDROCARBONS - An organic chemical compound containing mainly the elements carbon and hydrogen. Aliphatic hydrocarbons are straight chain compounds of carbon and hydrogen. Aromatic hydrocabons are carbon-hydrogen compounds based on the cyclic or benzene ring. They may be gaseous (CH_4, ethylene, butadiene), liquid (hexene, benzene), or solid (natural rubber, napthalene, cis-polybutadiene) (Goodrich, 1979).

HYDROGEN SULFIDE - (H_2S) - A poisonous gas with the odor of rotten eggs that is produced from the reduction of sulfates and the putrefaction of sulfur containing organic matter (EPA, 1977).

ORGANIC CONTENT - Usually synonymous with volatile solids in an ashing test; a discrepancy between volatile solids and organic content can be caused by small traces of some inorganic materials such as calcium carbonate that lose weight at temperatures used in determining volatile solids (EPA, 1972).

OSMOSIS - The diffusion which proceeds through a semipermeable membrane typically separating two solutions, or a solvent and a solution, and tending to equalize their concentrations. The net movement in osmosis is diffusion of solvent into the more concentrated solution (Webster's New Collegiate Dictionary).

pH - (1) The negative log of the hydrogen ion concentration, a measure of acidity and alkalinity (EPA, 1972). (2) A measure of the relative acidity or alkalinity of water. A pH of 7.0 indicates a neutral condition. A greater pH indicates alkalinity and a lower pH, acidity. A one unit change in pH indicates a tenfold change in acidity and alkalinity.

SOLUBILITY - The amount of a substance which will dissolve in a given amount of another substance (Webster's New Collegiate Dictionary).

SUSPENDED SOLIDS - Solids that either float on the surface of or are in suspension in water, wastewater, or other liquids, and which are largely removable by laboratory filtering as described in "Standard Methods of the Examination of Water and Wastewater", and referred to as nonfilterable residue (EPA, 1977).

VOLATILE ACIDS - Lower acids up to and including capric acid, which are volatile, will vaporize, evaporate, or distill off, with steam (Bennett, 1947).

VOLATILE SOLIDS - The material lost from a dried solid waste sample that is heated until it is red in an open crucible in a ventilated furnace. The weight of volatile solids is equal to that of the volatile matter plus that of the fixed carbon (EPA, 1972).

GLOSSARY

HAZARDOUS WASTE MANAGEMENT

ACIDIC WASTE - A waste that has a low pH.

AERATION SYSTEM - A system which exposes a bulk material, such as a compost, to air, or which charges a liquid with a gas or a mixture of gases (EPA, 1972).

BIODEGRADABLE - Susceptible to decomposition as a result of attack by microorganisms - said of organic materials (Hempel and Hawley, 1976).

CHEMICAL FIXATION - Treatment process which involves reactions between the waste and certain chemicals, and which results in solids which encapsulate, immobilize or otherwise tie up hazardous components in the waste so as to minimize the leaching of hazardous components and render the waste nonhazardous or more suitable for disposal.

COLLECTION (DRAINAGE) SYSTEM - Structures and facilities for collecting and carrying away water or other liquids (Asphalt Institute, MS-15).

COMPATIBILITY - Capability of existing together without adverse effects. Applied primarily to combinations of waste fluids and liner materials.

FACILITY - Any land and appurtenances thereon and thereto, used for treatment, storage and/or disposal of hazardous waste (Fed. Regist., 1978).

FLY ASH - All solids, including ash, charred paper, cinders, dust, soot, or other partially incinerated matter that are carried in a gas stream (EPA, 1972).

HAZARDOUS WASTE - A solid waste or combination of solid wastes, which because of its quantity, concentration or physical, chemical, or infectious characteristics may:

a. cause, or significantly contribute to an increase in mortality or an increase in serious irreversible, or incapacitating reversible, illness; or

b. pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported, or disposed of, or otherwise managed (Public Law 94-580, 1976).

HEAVY METALS - A general name given to the ions of metallic elements such as copper, zinc, chromium, or aluminum. They are normally removed from a wastewater by forming an insoluble precipitate, usually a metallic hydroxide (EPA, 1977).

HERBICIDE - A type of pesticide, including so called weed-killers, silvicides, and defoliants, which kills or otherwise eliminates shrubs, small trees, grasses, etc. There are both organic and inorganic herbicides: the latter is typified by common salt, sodium borate, and various arsenical compounds; the former by 2, 4-D and similar chlorinated compounds and by the defoliant picloram (EPA, 1977).

IMPOUNDMENT - See "Surface Impoundment" in Site Construction Glossary.

INDUSTRIAL WASTE - The liquid wastes from industrial processes as distinct from domestic or sanitary waste (EPA, 1977).

LEACHATE - See Solid Waste Management Glossary.

LINER - See Solid Waste Management Glossary.

MONITORING - All systematic procedures used to inspect and collect data on operational parameters of a facility or on the quality of the air, groundwater, surface water or soil.

MONITORING WELL - A well used to obtain water samples for water quality analysis or to measure groundwater levels.

PESTICIDE - See Solid Waste Management Glossary.

SOLID WASTE - See Solid Waste Management Glossary.

SUMP - A pit or well in which liquids collect (Webster's New World Dictionary).

TOXICANT - A toxic agent, especially one for insect control, that kills rather than repels (Webster's Collegiate Dictionary).

TOXIN - (1) Any of various unstable poisonous compounds produced by some microorganisms and which cause certain diseases. (2) Any of various similar poisons, related to proteins, secreted by plants and animals (Webster's New World Dictionary).

GLOSSARY

HYDROLOGY

AQUIFER - A geologic formation, group of formations, or part of a formation that is capable of yielding usable quantities of groundwater to wells or springs (Fed. Regist., 1978).

CAPILLARY WATER - Underground water that is held above the water table by capillary action (EPA, 1972).

DISSOLVED SOLIDS - Solids or particles small enough to be part of a solution. Dissolved solids will pass through a glass fiber filter (APHA - AWWA - WPCF 1975).

FLUX - (1) A bituminous material (generally liquid) used for softening other bituminous materials. (2) The rate of flow of a solute through a porous medium; or more technically, the volume of flow per unit time per unit area perpendicular to the direction of flow referred to as the Darcian velocity of flux density (Fuller, 1978).

GROUNDWATER, FREE - (1) Groundwater in aquifers. (2) Water in the saturated zone beneath the land surface (Fed. Regist., 1978).

HEAD, (PRESSURE) - Pressure measured as an equivalent height of water.

HYDRAULIC GRADIENT - The change in hydraulic pressure per unit of distance in a given direction.

HYDROLOGY - Science dealing with the properties, distribution, and flow of water on or in the earth (EPA, 1972).

RUN OFF - That portion of precipitation or irrigation water that drains from an area as surface flow (EPA, 1972).

SLOPE - Deviation of a surface from the horizontal expressed as a percentage, by a ratio, or in degrees (EPA, 1972).

WATER TABLE - (1) The upper limit of the part of the soil or underlying rock material that is wholly saturated with water (EPA, 1972). (2) The upper surface of the zone of saturation in groundwaters in which the hydrostatic pressure is equal to atmospheric pressure (Fed. Regist., 1978).

WATER TABLE, PERCHED - A water table, usually of limited area, maintained above the normal free-water elevation by the presence of an intervening, relatively impervious stratum (EPA, 1972).

ZONE OF AERATION - Area above a water table where the interstices (pores) are not completely filled with water (EPA, 1972).

ZONE OF CAPILLARITY - The area above a water table where some or all of the interstices (pores) are filled with water that is held by capillary action (EPA, 1972).

GLOSSARY

POLYMERIC MEMBRANE LINER TECHNOLOGY

ADHESION - The state in which two surfaces are held together by interfacial forces which may consist of molecular forces or interlocking action or both. Measured in shear and peel modes. (Goodrich, 1979).

AIR LANCE - A device used to test, in the field, the integrity of field seams in plastic sheeting. It consists of a wand or tube through which compressed air is blown.

ALLOYS, POLYMERIC - A blend of two or more polymers, e.g. a rubber and a plastic, to improve a given property, e.g. impact strength.

ANCHOR TRENCH - A long narrow ditch on which the edges of a plastic sheet are buried to hold it in place or to anchor the sheet.

BERM - The upper edge of a pit or pond where a membrane liner is anchored. The berm may be wide and solid enough for vehicular traffic.

BLOCKING - Unintentional adhesion usually occurring during storage or shipping between plastic films or between a film and another surface (ASTM D883).

BODIED SOLVENT ADHESIVE - An adhesive consisting of a solution of the liner compound used in the seaming of liner membranes.

BOOT - A bellows type covering to exclude dust, dirt, moisture, etc., from a flexible joint (Goodrich, 1979).

BREAKING FACTOR - Tensile at break in force per unit of width; units, SI: Newton per meter, customary: pound per inch.

BUTYL RUBBER - A synthetic rubber based on isobutylene and a minor amount of isoprene. It is vulcanizable and features low permeability to gases and water vapor and good resistance to aging, chemicals, and weathering.

CALENDER - A precision machine equipped with three or more heavy internally heated or cooled rolls, revolving in opposite directions. Used for preparation of highly accurate continuous sheeting or plying up of rubber compounds and frictioning or coating of fabric with rubber or plastic compounds (Goodrich, 1979).

CHLORINATED POLYETHYLENE (CPE) - Family of polymers produced by chemical reaction of chlorine on the linear backbone chain of polyethylene. The resultant rubbery thermoplastic elastomers presently contain 25-45% chlorine by weight and 0-25% crystallinity. CPE can be vulcanized but is usually used in a nonvulcanized form.

CHLOROSULFONATED POLYETHYLENE (CSPE) - Family of polymers that are produced by polyethylene reacting with chlorine and sulfur dioxide. Present polymers contain 25-43% chlorine and 1.0-1.4% sulfur. They are used in both vulcanized and nonvulcanized forms. Most membranes based on CSPE are nonvulcanized (ASTM designation for this polymer is CSM).

COATED FABRIC - Fabrics which have been impregnated and/or coated with a rubbery or plastic material in the form of a solution, dispersion, hotmelt, or powder. The term also applies to materials resulting from the application of a preformed film to a fabric by means of calendering.

CREEP - The slow change in length or thickness of a material under prolonged stress.

CROSSLINKING - A general term referring to the formation of chemical bonds between polymeric chains to yield an insoluble, three dimensional polymeric structure. Crosslinking of rubbers is vulcanization (q.v.).

CURING - See "Vulcanization".

DENIER - A unit used in the textile industry to indicate the fineness of continuous filaments. Fineness in deniers equals the mass in grams of 9000 meter length of the filament.

DIELECTRIC SEAMING - See "Heat Seaming".

ELASTICITY - The property of matter by virtue of which it tends to return to its original size and shape after removal of the stress which caused the deformation (Goodrich, 1979).

ELASTOMER - See "Rubber".

EPDM - A synthetic elastomer based on ethylene, propylene and a small amount of a non-conjugated diene to provide sites for vulcanization. EPDM features excellent heat, ozone and weathering resistance and low temperature flexibility.

EPICHLOROHYDRIN RUBBER - This synthetic rubber includes two epichlorohydrin-based elastomers which are saturated, high molecular weight, aliphatic polyethers with chloro-methyl side chains. The two types include a homopolymer (CO) and a copolymer of epichlorohydrin and ethylene oxide (ECO) These rubbers are vulcanized with a variety of reagents that react difunctionally with the chloromethyl group; including diamines, urea, thioureas, 2-mercaptoimidazoline, and ammonium salts.

EXTRUDER - A machine with a driven screw for continuous forming of rubber by forcing through a die; can be used to manufacture films and sheeting.

EVA - Family of copolymers of ethylene and vinyl acetate used for adhesives and thermoplastic modifiers. They possess a wide range of melt indexes.

FABRIC-REINFORCEMENT - A fabric, scrim, etc., used to add structural strength to a 2 or more ply polymeric sheet. Such sheeting is referred to as "supported".

FILL - As used in textile technology refers to the threads or yarns in a fabric running at right angles to the warp. Also called filler threads. (Rubber Manufacturers Assn., 1969).

FILM - Sheeting having nominal thickness not greater than 10 mils (ASTM, D883).

HEAT SEAMING - The process of joining two or more thermoplastic films of sheets by heating areas in contact with each other to the temperature at which fusion occurs. The process is usually aided by a controlled pressure. In dielectric seaming the heat is induced within films by means of radio frequency waves.

LAPPED JOINT - A joint made by placing one surface to be joined partly over another surface and bonding the overlapping portions (Whittington, 1968).

LENO FABRIC - An open fabric in which two warp yarns wrap around each fill yarn in order to prevent the warp or fill yarns from sliding over each other.

MEMBRANE - In this Manual the term membrane applies to a continuous sheet of material whether it is prefabricated as a flexible polymeric sheeting or is sprayed or coated in the field, such as a sprayed-on asphalt.

MODULUS - The stress on stretching a material to different elongations, e.g. s-100% and s-200%.

MODULUS OF ELASTICITY - The ratio of stress to strain within the elastic range, also known as Young's modulus (ASTM, 1972).

NEOPRENE (POLYCHLOROPRENE) - Generic name for a synthetic rubber based primarily on chloroprene, i.e. chlorobutadiene. Vulcanized generally with metal oxide. Resistant to ozone and aging and to some oils.

NITRILE RUBBER - A family of copolymers of butadiene and acrylonitrile that can be vulcanized into tough oil resistant compounds. Blends with PVC are used where ozone and weathering are important requirements in addition to its inherent oil and fuel resistance.

NYLON - Generic name for a family of polyamide polymers characterized by the presence of the amide group $-CONH_2$. Used as a scrim in fabric reinforced sheeting (Cond. Chem. Dict., 1977).

PERMEABILITY - (1) The capacity of a porous medium to conduct or transmit fluids (ASCE,1976). (2) The amount of liquid moving through a barrier in a unit time, unit area, and unit pressure gradient not normalized for but directly related to thickness (Wren, 1973).

PLASTIC - A material that contains as an essential ingredient one or more organic polymeric substances of large molecular weight, is solid in its finished state and at some stage in its manufacture or processing into finished articles, can be shaped by flow (ASTM D883).

PLASTICIZER - A plasticizer is a material, frequently "solvent-like", incorporated in a plastic or a rubber to increase its ease of workability, its flexibility, or distensiblity. Adding the plasticizer may lower the melt viscosity, the temperature of the second order transition, or the elastic modulus of the polymer.

Plasticizers may be monomeric liquids (phthalate esters), low molecular weight liquid polymers (polyesters) or rubbery high polymers (EVA).

The most important use of plasticizers is with PVC where the choice of plasticizer will dictate under what conditions the liner may be used.

POLYESTER FIBER - Generic name for a manufactured fiber in which the fiber-forming substance is any long chain synthetic polymer composed of an ester of a dihydric alcohol and terephthalic acid. Scrims made of polyester fiber are used for fabric reinforcement.

POLYMER - A macromolecular material formed by the chemical combination of monomers having either the same or different chemical composition. Plastics, rubbers, and textile fibers are all high molecular weight polymers.

POLYMERIC LINER - Plastic or rubber sheeting used to line disposal sites, pits, ponds, lagoons, canals, etc.

POLYVINYL CHLORIDE (PVC) - A synthetic thermoplastic polymer prepared from vinylchloride. PVC can be compounded into flexible and rigid forms through the use of plasticizers, stabilizers, fillers, and other modifiers; rigid forms used in pipes and well screens; flexible forms used in manufacture of sheeting.

PUNCTURE RESISTANCE - Extent to which a material is able to withstand the action of a sharp object without perforation. Examples of test of this property are Federal Test Method Standard No. 101B, Methods 2031 or 2065.

ROLL GOODS - A general term applied to rubber and plastic sheeting whether fabric reinforced or not. It is usually furnished in rolls.

RUBBER - A polymeric material which, at room temperature, is capable of recovering substantially in shape and size after removal of a deforming force. Refers to both synthetic and natural rubber. Also called an elastomer.

SCRIM - A woven, open mesh reinforcing fabric made from continuous filament yarn. Used in the reinforcement of polymeric sheeting (Whittington, 1968).

SEAM STRENGTH - Strength of a seam of liner material measured either in shear or peel modes. Strength of the seams is reported either in absolute units, e.g. pounds per inch of width, or as a percent of the strength of the sheeting.

SHEETING - A form of plastic or rubber in which the thickness is very small in proportion to length and width and in which the polymer compound is present as a continuous phase throughout, with or without fabric.

STRIKETHROUGH - A term used in the manufacture of fabric-reinforced polymeric sheeting to indicate that two layers of polymer have made bonding contact through the scrim.

SUPPORTED SHEETING - See "Fabric-Reinforcement".

SURFACE CURE - Curing or vulcanization which occurs in a thin layer on the surface of a manufactured polymeric sheet or other items.

TEAR STRENGTH - The maximum force required to tear a specified specimen, the force acting substantially parallel to the major axis of the test specimen. Measured in both initiated and uninitiated modes. Obtained value is dependent on specimen geometry, rate of extension, and type of fabric reinforcment. Values are reported in stress, e.g. pounds, or stress per unit of thickness, e.g. pounds per inch.

TENSILE STRENGTH - The maximum tensile stress per unit of original cross-sectional area applied during stretching of a specimen to break; units: SI-Mega on kilopascal, customary - pound per square inch.

THERMOPLASTIC - Capable of being repeatedly softened by increase of temperature and hardened by decrease in temperature. Most polymeric liners are supplied in thermoplastic form because the thermoplastic form allows for easier seaming both in the factory and on the field.

THERMOPLASTIC ELASTOMERS - New materials which are being developed, and which are probably related to elasticized polyolefins. Polymers of this type behave similarly to cross linked rubber. They have a limited upper temperature service range which, however, is substantially above the temperature encountered in waste disposal sites (200°F may be too high for some TPE's).

THREAD COUNT - The number of threads per inch in each direction with the warp mentioned first and the fill second, e.g. a thread count of 20 x 10 means 20 threads per inch in the warp and 10 threads per inch in the fill direction.

ULTIMATE ELONGATION - The elongation of a stretched specimen at the time of break. Usually reported as percent of the original length. Also called elongation at break.

UNSUPPORTED SHEETING - A polymeric sheeting consisting of one or more plies without a reinforcing fabric layer or scrim.

VACUUM BOX - A device used to assess the integrity of field seams in membrane liners.

VULCANIZATE - Used to denote the product of the vulcanization of a rubber compound without reference to shape or form.

VULCANIZATION - An irreversible process during which a rubber compound, through a change in its chemical structure, e.g. crosslinking, becomes less plastic and more resistant to swelling by organic liquids, and during which elastic properties are conferred, improved, or extended over a greater range of temperature (ASTM, 1972).

WARP - In textiles, the lengthwise yarns in a woven fabric (Rubber Manufacturers Assn., 1969).

WATER VAPOR TRANSMISSION (WVT) - Water vapor flow normal to two parallel surfaces of a material, through a unit area, under the conditions of a specified test such as ASTM E96.

GLOSSARY

SITE CONSTRUCTION

ANCHOR TRENCH - See "Polymeric Membrane Liner Technology Glossary".

BLADE - A heavy broad metal plate attached to the front of a tractor.

- U-"Universal" - A blade with extensions on each side that protrude forward at an obtuse angle to the blade and enable it to handle a larger volume than a regular blade.
- Landfill: A U-blade with an extension on top that increases the volume of solid wastes that can be pushed and spread, and protects the operator from debris thrown out of the solid waste.

COURSE - See "Lift".

COVER, FINAL - The cover material that is applied at the end of the useful life of a disposal site and represents the permanently exposed final surface of the fill.

COVER MATERIAL - A soil or other suitable material that is used to cover the liner or wastes in a disposal site.

CUT AND COVER (CUT AND FILL) - An infrequently and incorrectly used term referring to the trench method of sanitary landfilling (EPA, 1972).

CUT-OFF TRENCH - A trench that is filled with material that may be impermeable or very permeable to the flow of gas or water. The barrier is used to prevent the movement of gas or water or to intercept and to direct them to another location (EPA, 1972).

DRAINAGE - Provision for directing the runoff that occurs from precipitation or overland flow in such a way as to prevent contact with refuse or interference with landfill operations (ASCE, 1976).

EARTHEN DIKE - A dam constructed of soil and earth.

GEOTEXTILE - A textile fabric, such as a filter fabric used in civil engineering applications.

GRADE - (1) See "Gradient". (2) To level off to a smooth horizotal or sloping surface. (3) A datum or reference level. (4) Particle sized distribution of an aggregate.

GRADIENT - The degree of slope or a rate of change of a parameter measured over distance (EPA, 1972).

GROUT - A cementing or sealing mixture of cement and water to which sand, sawdust or other fillers may be added (EPA, 1972).

IMPOUNDMENT - See "Surface Impoundment".

LIFT - A single layer of compacted soil. Lift thickness depends on soil and degree of compaction needed (also termed "course").

ROLLER - A heavy cylinder of metal, stone, etc., used to crush, compact, or smooth a surface (Webster's New World Dict.).

SEEPAGE - Movement of water or gas through soil without forming definite channels (EPA, 1972).

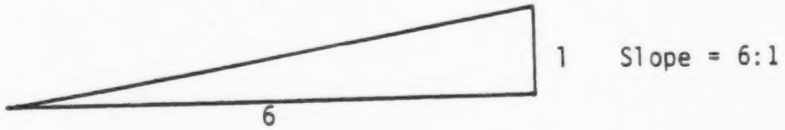
SETTLEMENT - A gradual subsidence of material (EPA, 1972).

SETTLEMENT DIFFERENTIAL - Nonuniform subsidence of material from a fixed horizontal reference plane (ASCE, 1976). More commonly known as "Differential Settlement".

SHEEPSFOOT ROLLER - A tamping roller with numerous closely spaced "feet", or solid cylinders, approximately 6 inches long and with a tamping area of about 7 square inches. It is often used in the compacting of soils. The weight of the roller when loaded and used is required by the Bureau of Reclamation to be not less than 4000 lb. per foot of length of drain (Bur. Rec., 1974).

SITE - Jobsite.

SLOPE - Deviation of a surface from the horizontal expressed as a percentage, by a ratio, or in degrees. In engineering, usually expressed as a ratio of horizontal:vertical change (EPA, 1972).



SPRAY BAR - a long hollow tube with nozzles of any of a number of forms, used to apply a thin layer or coat of a substance in liquid form. Spray bars are attached by hoses and pneumatic lines to pumps to convey the liquid from the storage truck or tank to the nozzles.

STABILIZATION - A stabilizing procedure, or to make stable, to firm, as applied to a soil.

SUBGRADE - The foundation or suppporting soil layer for a liner. Subgrades can be the surface of the upgraded native soil, but are more commonly specially prepared, artificially compacted layers of soil.

SUBSIDENCE - Settling or sinking of the land surface due to many factors such as the decomposition of organic material, consolidation, drainage, and underground failure (EPA, 1972).

SUBSOIL - That part of the soil beneath the topsoil, usually not having an appreciable organic matter content (EPA, 1972).

SURFACE COMPACTION - Increasing the dry density of surface soil by applying a dynamic load (EPA, 1972).

SURFACE CRACKING - Discontinuities that develop in the cover material at a sanitary landfill due to the surface drying of the cover or settlement of the solid waste. Such discontinuities can permit entrance or egress of vectors, intrusion of water, and venting of decomposition gases (EPA, 1972).

SURFACE IMPOUNDMENT - A natural topographic depression, artificial excavation, or dike arrangement with the following characteristics: (1) it is used primarily for holding, treatment, or disposal of waste; (2) it may be constructed above, below, or partially in the ground or in navigable waters (e.g., wetlands); and (3) it may or may not have a permeable bottom and/or sides. Examples include holding ponds and aeration ponds (Fed. Regist., 1978).

VENT - An opening to permit passage or escape of a gas or liquid (Webster's New World Dictionary).

GLOSSARY

SOIL SCIENCE AND ENGINEERING

AIR DRY - (1) The state of dryness (of a soil) at equilibrium with the moisture content in the surrounding atmosphere. The actual moisture content will depend on the relative humidity and the temperature of the surrounding atmosphere. (2) To allow to reach equilibrium in moisture content with the surrounding atmosphere (SSSA, 1970).

AIR POROSITY - The proportion of the bulk volume of soil that is filled with air at any given time or under a given condition such as a specified moisture tension (SSA, 1970).

ALLUVIUM - A general term for all detrital material deposited or in transit by streams, including gravel, sand, silt, clay and all variations and mixtures of these. Unless otherwise noted, alluvium is unconsolidated (Brady, 1974).

AMPHOTERIC - Having the property of reacting with either an acid or a base. Many oxides and salts have this ability (aluminum hydroxide, for example) (Hampel and Hawley, 1976).

ANION EXCHANGE CAPACITY - The sum total of exchangeable anions that a soil can absorb. Expressed as milliequivalents per 100 gram of soil (or other absorbing materials such as clay) (SSSA, 1970).

ATTERBERG LIMITS - Moisture content values which are measured for soil materials passing a No. 40 sieve and which define soil plasticity properties. Also referred to as plasticity limits. The Atterberg limits are as follows:

> Shrinkage Limit (SL): The maximum water content at which a reduction in water content will not cause a decrease in the volume of the soil mass. This defines the arbitrary limit between the solid and semi-solid states.
>
> Plastic Limit (PL): The water content corresponding to an arbitrary limit between the plastic and semi-solid states of consistency of a soil.
>
> Liquid Limit (LL): The water content corresponding to the arbitrary limit between the liquid and plastic states of consistency of a soil (Brady, 1974).

BEDROCK - The solid rock underlying soils and the regolith at depths from zero (where exposed by erosion) to several hundered feet (Brady, 1974).

BENTONITE - A soft clay formed as a weathering product from volcanic ash and composed chiefly of the mineral montmorillonite. Sodium bentonite is notable for its ability to swell in water.

CATION EXCHANGE CAPACITY (CEC) - The sum total of exchangeable cations that a soil can absorb; sometimes called "total exchange capacity", "base-exchange capacity" or "cation absorption capacity". Expressed in milliequivalents per 100 grams of soil (or of other absorbing material such as clay).

CALIFORNIA BEARING RATIO (CBR) - The ratio of (1) the force per unit area required to penetrate a soil mass with a 3 square in. circular piston (approximately 2 in. diameter) at the rate of 0.05 in./min. to (2) the force per unit area required for corresponding penetration of a standard material. Also known as the bearing ratio of laboratory compacted soils (ASTM D653, D18833).

CLAY - Term is used in three ways: (1) Soil particles less than two micrometers in equivalent diameter. Cf. sand, silt (2) A secondary soil mineral formed through weathering of primary minerals or transported. Mainly aluminosilicates, some relevant characteristics are:

1. Large surface area.
2. Hydration/dehydration.
3. Cation exchange capacity.
4. Particles less than two micrometers.
5. Flocculation/dispersion.

(3) Soil material containing more than 40% clay, less than 45% sand and less than 40% silt.

CLAY MINERAL - (1) Naturally occurring inorganic crystalline material found in soils and other earthy deposits, the particles being of clay size, i.e. <2 μm in diameter. (2) Material as described under (3) but not limited by particle size (SSSA, 1970).

COEFFICIENT OF PERMEABILITY - See PERMEABILITY.

COHESION - that part of soil strength that is present independently of any applied pressures, either mechanical or capillary, and would remain, though not necessarily permanently, if all applied pressures were removed.

COMPACTION - Compression of a mass to decrease its volume or the thickness of a layer by reduction of voids.

DARCY'S LAW - A law describing the rate of flow of water through porous media.

DISPERSED STRUCTURE - A soil structure wherein the clay particles are associated primarily in a random, parallel array.

DOUBLE LAYER - In colloid chemistry, the electric charges on the surface of the disperse phase (usually negative), and the adjacent diffuse layer (usually positive) of ions in solution (SSSA, 1970).

EXCHANGEABLE SODIUM PERCENTAGE - The extent to which the absorption complex of a soil is occupied by sodium. It is expressed as follows:

$$\text{ESP} = \frac{\text{Exchangeable sodium (meq/100g soil)}}{\text{Cation-exchange capacity (meq/100g soil)}}$$

FLOCCULATED STRUCTURE - A soil structure wherein the clay particles are associated primarily in a random, predominantly edge-to-face arrangement with essentially solid contact in the areas of closest approach.

GRAVITATIONAL WATER - Water which moves into, through, or out of the soil under the influence of gravity.

HYDRAULIC CONDUCTIVITY - See "Permeability".

ILLITE - A major group of clay minerals having the crystalline structure of hydrous mica.

INFILTRATION RATE (INFILTRATION CAPACITY) - A soil characteristic determining the maximum rate at which water can enter the soil under specified conditions, including the presence of an excess of water. It has the dimensions of velocity (SSSA, 1970).

INFILTRATION VELOCITY - The actual rate at which water is entering the soil at any given time. It may be less than the maximum (the infiltration rate) because of a limited supply of water (rainfall or irrigation). It has the same units as infiltration rate (SSSA, 1970).

INTRINSIC PERMEABILITY - The property of a porous material that relates to the ease with which gases or liquids can pass through it. The Darcy "K" is multiplied by n'/g to obtain K', the intrinsic permeability, where:

n' is the kinematic viscosity of the fluid in $\text{cm}^2\ \text{sec}^{-1}$

g is the acceleration of gravity in cm/sec^2

$n' = n/p$
where, n is viscosity in poises, $\text{g cm}^{-1}\ \text{sec}^{-1}$
p is density of the fluid in g cm^{-3}

For water at 23°C and g = 981 cm sec^{-1}, the relationship between permeability, K, and intrinsic permeability K' is expressed by the equation

$$K' = (0.91 \times 10^{-5}\ \text{cm sec})(K)$$

INTERLAYER - Materials between layers, including cations, hydrated cations, organic molecules and hydroxide groups or sheets. Refers to clay mineralogy microstructure (SSSA, 1970).

INTERLAYER (OR BASAL) SPACING - The space between layers in clay microstructure.

ISOMORPHOUS SUBSTITUTION - The replacement of one atom by another of similar size and lower charge (valance) in crystal lattice without significantly disrupting or changing the crystal structure of the mineral (SSSA, 1970).

ISOTROPIC SOIL - A soil in which a certain property at a point is the same in all directions through that point.

KAOLIN - (1) An alumino-silicate mineral of the 1:1 crystal lattice group; that is, consisting of one silicon tetrahedral layer and one aluminum oxide-hydroxide octahedral layer. (2) The 1:1 group or family of alumino-silicates (SSSA, 1970).

LOAM - A textural class name for soil having a moderate amount of sand, silt, and clay. Loam soils contain 7-28% clay, 28-50% silt, and less than 52% sand (Brady, 1974).

MOISTURE CONTENT - The weight loss (expressed in %) when a sample of soil or waste is dried to a constant weight at 100-105°C (EPA, 1972).

MOISTURE CONTENT, OPTIMUM - The water content at which a soil-like mass can be compacted to a maximum dry unit weight by a given compactive effort.

MOISTURE RETENTION CURVE - A graph showing the soil moisture percentage (by weight or by volume) versus applied tension. Points on the graph are obtained by increasing or decreasing the applied tension over a specified range (SSSA, 1970).

MOISTURE TENSION (OR PRESSURE) - The equivalent negative pressure in the soil water. It is the equivalent pressure that must be applied to the soil water to bring it to hydraulic equilibrium, through a porous permeable wall or membrane, with a pool of water of the same composition (SSSA, 1970).

MOISTURE-WEIGHT PERCENTAGE - The moisture content expressed as a percentage of the oven-dry weight of soil (SSSA, 1970).

MONTMORILLONITE - An alumino-silicate clay mineral with a 2:1 expanding crystal structure; that is, with two silicon tetrahedral layers enclosing an aluminum octahedral layer. Considerable expansion may be caused along the axis by water moving between the silica tetrahedra of neighboring layers.

OVENDRY SOIL - Soil which has been dried at 105°C until it reaches a constant weight (SSSA, 1970).

PARTICLE DENSITY - The mass per unit volume of the soil particles. In technical work, usually expressed as g/cm^3 (SSSA, 1970).

PARTICLE SIZE - The effective diameter of a particle measured by sedimentation, sieving, or micrometric methods (SSSA, 1970).

PARTICLE SIZE DISTRIBUTION - The amounts of the different soil particles in a soil sample, usually expressed in weight percentages (SSSA, 1970).

PERCOLATION, SOIL WATER - Downward movement of water through soil. Especially, the downward flow of water in saturated or near saturated soil at hydraulic gradients of the order of 1.0 or less (SSSA, 1970) (ASTM, D653, 1979).

PERMEABILITY - A numerical measure of the ability of a soil to transmit a fluid (typically water). Permeability, K, is a constant of proportionality uder conditions of laminar flow, such that the Darcy relationship is valid. Permeability has dimensions of velocity, i.e. cm sec^{-1}.

PLASTICITY INDEX (PLASTICITY NUMBER) (PLASTICITY RANGE) - The numerical difference between the liquid limit and the plastic limit.

PLASTIC LIMIT - See Atterberg limits.

PLATY - Consisting of soil aggregates that are developed predominantly along horizontal axes; laminated, flaky (SSSA, 1970).

PORE-SIZE DISTRIBUTION - The volume of various sizes of pores in a soil. Expressed as a percentage of bulk volume, i.e., total volume of solids and pores (SSSA, 1970).

POROSITY - The volume percentage of the total bulk not occupied by solid particles (SSSA, 1970).

POTASSIUM FIXATION - The process of converting exchangeable to nonexchangeable potassium (adapted from SSSA, 1970).

PROCTOR (COMPACTION TEST) - Standard proctor or standard AASHTO test used to determine the proper amount of mixing water to use when compacting a soil test in the field and the resulting degree of density which can be expected from compaction at this optimum water content (Lambe, 1951).

SAND - Coarse grain soils of which more than half of the coarse fraction is smaller than 4.75 mm sieve size (Unified Soil Classification).

SANDY LOAM - A soft easily worked soil containing 0-20% clay, 0-5% silt and 43-85% sand according to the US Department of Agriculture (EPA, 1972).

SHRINK/SWELL - Volume change due to build-up and release of capillary tensile stress within the soil's pore water (Asphalt Institute, MS-10).

SILT - (1) Soil particles which pass through a No. 200 sieve and are larger than 0.002 mm in equivlant diameter. (2) Soil textural class (Brady, 1974).

SMECTITE - See Montmorillonite.

SOIL - The unconsolidated natural surface material present above bedrock; either residual in origin (formed by the in-place weathering of bedrock) or placed by the wind, water, or gravity (EPA, 1972).

SOIL PIPING OR TUNNELING - Accelerated erosion which results in subterranean voids and tunnels (SSSA, 1970).

SOIL SOLUTION - The aqueous liquid phase of the soil and its solutes consisting of ions dissociated from the surfaces of the soil particles and of other soluble materials (Brady, 1974).

SOIL STRUCTURE - The combination or arrangement of primary soil particles into secondary particles, units, or peds. These secondary units may be, but usually are not, arranged in the profile in such a manner as to give a distinctive characteristic pattern. The secondary units are characterized and classified on the basis of size, shape, and degree of distinctness into classes, types, and grades, respectively (SSSA, 1970).

SOLUM - The upper and most weathered part of the soil profile; the A and B horizons (SSSA, 1970).

SURFACE SEALING - The orientation and packing of dispersed soil particles in the immediate surface layer of the soil, rendering it relatively impermeable to water (SSSA, 1970).

TACTOID - An agglomeration of clay particles.

TEXTURE - The relative proportions of various particle size classes (clay, silt, sand) in a soil (Brady, 1974).

THIXOTROPY - An isothermal, reversible, time-dependent process occurring under conditions of constant composition and volume whereby a material stiffens while at rest and softens or liquifies upon remolding (Mitchell, 1960).

UNSATURATED FLOW - The movement of water in a soil which is not filled to capacity with water (SSSA, 1970).

VOID RATIO - Volumetric proportion in a bulk volume of soil between voids and solid soil.

WATER STABLE AGGREGATE - A soil aggregate which is stable to the action of water such as falling drips or agitation, as in wet sieve analysis (SSSA, 1970).

GLOSSARY

SOLID WASTE MANAGEMENT

AQUIFER - See Hydrology Glossary.

BIODEGRADABLE - See Hazardous Waste Glossary.

BOD_5 - See Chemistry Glossary.

CELL - Portion of waste in a landfill which is isolated horizontally and vertically from other portions of waste in the landfill by means of soil barrier (Fed. Regist., 1978).

COD - See Chemical Glossary.

COLLECTION SYSTEM - See Hazardous Waste Glossary.

COMPATIBILITY - See Hazardous Waste Glossary.

COVER, DAILY - The cover material that is applied over compacted wastes in a working landfill at the end of each operating day.

DENSITY -

Sanitary Landfill: Ratio of the combined weight of solid waste and the soil cover to the combined volume of the solid waste and the soil cover:

$$\frac{W_{SW} + W_{soil}}{V_{SW} + V_{soil}}$$

Solid Waste: The number obtained by dividing the weight of solid waste by its volume (EPA, 1972).

EFFLUENT (1) A liquid which flows out of a containing space; (2) Sewage water or other liquids partially or wholly flowing out of a reservoir basin or treatment plant or part therof (EPA, 1977).

FACILITY - Any land or appurtenances thereon and thereto, used for treatment, storage and/or disposal of hazardous waste (Fed. Regist., 1978).

FIELD CAPACITY - The maximum amount of moisture a soil or solid waste can retain in a gravitational field without a continuous downward percolation (Fenn et al, 1975).

IMPERMEABLE- Not permitting passage of a fluid or a gas through its substance.

IMPERVIOUS - See "Impermeable".

INDUSTRIAL WASTE - See Hazardous Waste Glossary.

LEACHATE - Liquid that has percolated through or drained from hazardous waste or other man-emplaced materials and contains soluble, partially soluble, or miscible components removed from such waste (Fed. Regist., 1978). Primary leachate, as used in this document is that liquid originating in the waste; secondary leachate is that liquid which enters the waste and percolates through.

LINER - A layer of emplaced materials beneath a surface, impoundment, or landfill which serves to restrict the escape of waste or its constituents from the impoundment or landfill (Fed. Regist., 1978). In this Technical Resource Document, a liner includes: reworked or compacted soil and clay, asphaltic and concrete materials, spray-on membranes, polymeric membranes, chemisorptive substances, or any substance that serves the above stated purpose.

LYSIMETER - A device used to measure the quantity or rate of water movement through or from a block of soil or other material, such as solid waste, or used to collect percolated water for qualitative analysis (EPA, 1972).

MONITORING WELL - See Hazardous Waste Glossary.

MUNICIPAL SOLID WASTE - Solid waste collected from residential and commercial sources in bins and other large containers. Typical components are: plant matter, 1%; paper products, 56%; food wastes, 9%; metals, 8%; ceramics and glass, 8%; plastic , leather, and rubber, 4%; wood, rags, etc.; 7%.(Baum and Parker, 1974).

PESTICIDE - A broad term that includes all chemical agents used to kill animal and vegetable life which interfere with agricultural productivity, regardless of their mode of action (Hampel and Hawley, 1976).

pH - See Chemistry Glossary.

POLLUTANT - (1) A substance, material, chemical, etc., that renders the carrier medium, i.e., a solid, liquid, or gas, unfit for industrial or domestic use, or presents a potential public health hazard. (2) In this Technical Resource Document, a pollutant is a substance or material that degrades the quality of, or, directly or indirectly, presents a hazard to all or any of the following sectors of the environment: water, groundwater, air, soil, plants, wildlife, or people.

RUN-OFF - See Hydrology Glossary.

SANITARY LANDFILL (LAND FILLING) - A site where solid waste is disposed of on land in a manner that protects the environment by spreading the waste in thin layers, compacting it to the smallest practical volume, and then covering it with soil by the end of the working day (EPA, 1972).

SANITARY LANDFILLING METHODS - Area, Quarry, Ramp, Trench, and Wet Areas,

Area: A method in which the wastes are spread and compacted on the surface of the ground and cover material is spread and compacted over them.

Quarry: Wastes are spread and compacted in a depression; cover material is generally obtained elsewhere.

Ramp: Cover material is obtained by excavating in front of the working area. A variation of this method is known as the progressive slope sanitary landfilling method.

Trench: Waste is spread and compacted in a trench; the excavated soil is spread and compacted over the waste to form the basic cell structure.

Wet Area: Used in a swampy area where precautions are taken to avoid water pollution before proceeding with the area method (EPA, 1972).

SOLID WASTE - Any garbage, refuse, or sludge from a waste treatment plant, water supply treatment plant, or air pollution control facility, and other discarded material, including solid, liquid, semisolid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations, and from community activities; does not include solid or dissolved material in domestic sewage, or solid or dissolved materials in irrigation return flows or industrial discharges (Public Law, 1976).

SOLID WASTE MANAGEMENT - The purposeful, systematic control of the generation, storage, collection, transportation, separation, processing, recycling, recovery, and disposal of solid waste (EPA, 1972).

SUSPENDED SOLIDS - See Chemistry Glossary.

TOE - Bottom of any slope, specifically applied in this Manual to the bottom of the working face of a landfill.

VECTOR - A carrier, e.g. an insect or a rodent, that is capable of transmitting a pathogen from one organism to another (ASCE, 1976).

VOLATILE ACIDS - See Chemistry Glossary.

VOLATILE MATTER - The matter lost from a dry solid waste sample that is heated until it is red in a closed crucible (EPA, 1972).

VOLATILE SOLIDS - Chemistry Glossary.

WATER TABLE - See Hydrology Glossary.

WORKING FACE - That portion of a sanitary landfill where waste is discharged by collection trucks and is compacted prior to placement of cover material (EPA, 1972).

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